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Introduction

The effects of a warming climate on the terrestrial and marine regions of the Arctic are already becoming apparent; some subsequent impacts to the biologic, hydrologic, and human systems are also becoming evident. It is expected that the effects and consequences of a warming climate will become even more evident within the next 10 to 50 years. These changes will affect the Arctic Basin through impacts on regional weather, oceanic circulation patterns, salinity and temperature gradients, sea ice formation, and water properties. It is difficult to quantify the long-term effects of a changing climate, but it is possible to envision many of the changes that we should expect. In the last 50 years, a wide range of changes in the Arctic have been documented. Many of these changes were evident since the mid-1970s; however, it is quite likely that these changes began or were initiated early in the 20th century, prior to extensive observational records in arctic regions. Regardless of the driving forces, the combined observations and documentation suggest that the arctic system may be entering a state not seen before in historic times. The complex interplay of physical, chemical, biological, and social processes interact to such a degree that it is not possible to understand future trajectories without developing more fully holistic perspectives of the complete system. The components of the Arctic are inter-related through a complex network of linkages, feedbacks, and multi-dependent interactions. Our approach to understanding the arctic system has been to carefully examine the ongoing physical and biological processes and determine the underlying drivers and inherent linkages among system components. It is expected that development of a more integrated and comprehensive understanding of the arctic system will lead to an improved modeling capability and improved projections of future climate dynamics and system responses.

This report presents the results of the first year of collaborative projects among JAMSTEC and IARC researchers. We are working together to examine common problems of mutual interest to both Japan and the United States. We expect these collaborations will yield enhanced research projects by combining the intellectual resources of our collaborations.
Research Area 1: Arctic Ocean/ Sea Ice/Atmosphere
Theme 1: Monitoring of the Arctic Ocean Climate

Introduction
We continued our joint analysis of changes occurring in the Arctic Ocean. Our observations provided vital information about the state of the boundary current system, thus closing a substantial observational gap. For example, our observations demonstrated that a strong cooling tendency detected near Svalbard since 2006 is spreading over the Nansen Basin. These observations were particularly important in recent years because of the weak state of arctic ice, which precluded deployment of Lagrangian drifters in this part of the Arctic Ocean. New technology allowing survival of buoys deployed in seasonally ice-free areas is emerging, and we successfully deployed several buoys in ice-free areas of the eastern Eurasian Basin during 2009 summer expeditions. Information about Arctic Ocean water mass changes is critically needed to understand and assess the ocean’s role in climate change; our observations, therefore, are critical to the Arctic Ocean observational network.

Objectives
The objectives of this research are:
1. To provide new high-quality oceanographic data in areas of the Arctic Ocean where data coverage is low and oceanographic records are extremely rare.
2. To address key questions and problems associated with processes shaping water-mass structure and variability over multiple time scales.
3. To sharpen understanding of physical mechanisms behind the ocean-ice-air energy and mass exchange, which is critically important for predicting the future state of arctic ice and ocean.

For 2009 we planned:
1. To recover and deploy along-slope moorings and carry out a complementary oceanographic survey.
2. To continue analysis of newly available information collected during oceanographic cruises.

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Methodology
1. To recover and deploy along-slope moorings and carry out a complementary oceanographic survey.
2. To continue analysis of newly available information collected during
oceanographic cruises.
3. To coordinate international collaborations on Arctic Ocean monitoring especially on the mooring-based observation along the Atlantic Water pathway.

Planned activities for 2009FY

1. To recover and deploy along-slope moorings and carry out a complementary oceanographic survey.
2. To continue analysis of newly available information collected during oceanographic cruises.

Results of 2009FY

Our observations in previous years showed that the exceptional warming that entered the Eurasian Basin in 1999 progressed from Fram Strait along the Barents and Laptev slopes. This year CTD cross-sections carried out in the eastern and central Nansen Basin (Fig. 1) captured a transition from warming to strong cooling (~1°C) tendency in the western and central Eurasian Basin (Fig. 2).

![Fig. 1. NABOS observations in 2009.](image-url)
Fig. 2. Our joint observations provide evidence that unprecedented ongoing warming of the Arctic Ocean observed in the 2000s passed its tipping point.
Recent 2008–09 observations suggest that the ongoing warm surge passed its peak and the eastern Arctic Ocean is in transition to a cooler state. Stronger cooling of ≥1.5°C is found in the western Nansen Basin, near the origin of AW for the Arctic Ocean interior. Expectedly, weaker cooling of ~0.5°C or even less were documented further downstream from Fram Strait, in the eastern Eurasian Basin (Fig. 3). Comparison of CTD observations carried out north of Franz Josef Land (~60°E) in 2007 and 2009 was ~0.4°C (not shown) providing further confirmation for this cooling tendency.

A point-to-point comparison of the available temperature records suggests that it takes the anomaly slightly longer than a month to travel from Fram Strait to the northeastern vicinity of Svalbard (30°E) at an advection speed of ~20cm/s, thus confirming previous analogous estimates. According to the mooring and CTD records, the maximum temperature anomaly was observed at the Laptev Sea slope (125°E) sometime between September 2008 and September 2009, lagging the Fram Strait temperature peak by 2–3 years. If the cooling at 125°E was caused by advection of colder AW from the upstream locations, it suggests that the propagation speed should be much higher than ~1.5cm/s defined by the steep temperature increase at the beginning of the warm pulse. However, the pattern of anomalies propagating along the Siberian slope downstream from Fram Strait into the basin interior is not evident in the record from the easternmost location at the Lomonosov Ridge (140°E). There are several possible explanations for this. Almost synchronous retreat of the warm surge from the Fram Strait and eastern Eurasian Basin regions suggests that some other, non-advective forces strongly modulate temperature changes there. Probably local atmosphere-ocean and shelf-basin interactions influenced by anomalous openings in ice cover play the dominant role in ventilating the ocean’s interior in the eastern Eurasian Basin. The observed changes may also relate to changes in major pathways of the boundary current between the Eurasian and Canadian Basins.
Another factor important for the ventilation of AW is mixing with overlying layers. The 2009 observations provide an excellent opportunity to evaluate the upward spread of AW heat. Temperature (T) and salinity (S) profiles from four cross-isobath (>500m) sections spanning 60°E to 140°E were analyzed. The T-S diagram (Fig. 3) provides strong evidence that at low salinities (<34.3 psu, i.e., in the halocline and just below the upper mixed layer), temperatures are higher in eastern sections compared with western sections. AW heat warms even the uppermost layers (just beneath the upper mixed layer). For example, temperatures from the easternmost Laptev Sea section (142°E) were 0.1–0.2°C higher at 50–75 m than were western section temperatures (longitudes <110°E). The AW layer is the only source of heat for the overlying layer; therefore, this is strong evidence that upward heat flux from the AW occurs.

Observations provided critical information about the evolution of an unprecedentedly strong AW warm pulse from its entrance into the eastern Arctic Ocean as it decays along its path into the Eurasian Basin interior. Its fate in the Canadian Basin is still an open question. By analysis of a vast collection of observational data, we have shown the possible importance of AW warming for uptake of this heat by overlying layers (Fig. 3), with possible implications for an already-reduced arctic ice cover. Many mysteries still exist, explanations for which remain obscure and will require further investigation, but recent observations delivered valuable information about transitions occurring in the arctic climate system.

Presentations

Publications


In press


Submitted


In preparation
Research Area 1, Theme 2
Sea ice dynamics/thermodynamics observations in the Arctic Ocean

Introduction
The retreat of arctic sea ice extent during summer has attracted considerable attention from the public and science communities, especially since the record-shattering minimum set during the summer of 2007. A significant body of work has been done by others investigating mechanisms behind the recent sea ice retreat. There is general consensus that changes in ice drift pattern, air temperature, and cloud cover (related to changes in atmospheric circulation) are implicated. Changes in ocean circulation may also play a role, and Shimada et al. (2006) hypothesize a mechanism whereby weakening of the ice cover through thinning could lead to enhanced wind stress transfer to the ocean. This enhances intrusion of Pacific summer water into the Beaufort Sea, which leads to further thinning of the ice cover (a positive feedback). In order for this hypothesis to be correct, the sea ice deformation of a thinning ice pack must not act to increase ice pack thickness and strength through ridging. In other words, if deformation is implicated in a negative feedback on mass balance, the negative feedback must be smaller than the positive thermodynamic feedback. Deformation rates throughout the Arctic have been observed to be increasing since 1979 (Rampal et al., 2009). To date, the interaction between sea ice deformation and thermodynamic ice growth and melt has not been quantified. To quantify this relationship, we need to measure the impact of deformation on redistribution and level ice growth and relate this to variability in surface heat and moisture fluxes in summer.

In order to monitor the impact of sea ice deformation (and other mechanisms implicated in ice loss) on mass balance, we need to measure the mass of ice that survives to the end of summer. This requires accurate methods of monitoring ice area and thickness. The design of a sea ice deformation monitoring system relies on accurate deformation products as well as accurate mass balance estimates. Ice extent is well documented each summer. Ice area satellite products, on the other hand, suffer poor accuracy. It is critical that we develop reliable methods to monitor sea ice area, type, and thickness in the summer, and year-round ice deformation rates.

Objectives
Our objective is to quantify the dynamic-thermodynamic feedback of the arctic ice pack in recent years. As wintertime ice dynamics precondition the summer ice melt through control of the sea ice thickness distribution, ice dynamics provide a potential negative or positive feedback to sea ice mass balance.

Participants
Jennifer Hutchings (IARC), Takashi Kikuchi (JAMSTEC), Petra Heil (U. Tasmania), Andrew Roberts (IARC/ARSC), Ignatius Rigor (U. Washington), Alice Orlich (IARC), Bill Shaw (NPS), Jackie Richter-Menge (CRREL), Jamie Morrison (U. Washington), Hajo Eicken (UAF), Chris Petrich (UAF), Ron Lindsay (U. Washington).

Methodology
Characterize the mass balance of end-of-summer ice pack.
1. Obtain onboard ice observations during arctic summer cruises and analyze the observational data, which will provide in situ ice concentration and ice surface
condition (melt ponds, albedo information) to be able to validate passive microwave satellite end-of-summer ice concentration products.

2. Participate in CliC arctic ice observation coordination, to standardize arctic-wide ship observations, develop methods to extract data from ship-mounted cameras, and combine this information with remotely sensed data to build annual atlases of the end-of-summer ice conditions.

Understand the relationship between sea ice deformation and dynamics, ocean-atmosphere fluxes, and thermodynamic control of the ice mass balance.

1. To coordinate buoy deployments of IARC ice buoys and JAMSTEC ocean buoys (POPS) in collaboration with ice mass balance buoys from U.S. Navy Cold Region Research and Engineering Laboratory (CRREL). This will allow a detailed investigation of both dynamic evolution of sea ice thickness distribution and thermodynamic forcing on the ice.

2. Develop data (strain rate) driven models of sea ice redistribution that can be used to investigate the relationship between ice deformation and the sea ice mass balance.

Activities for 2009FY

In April 2009, we planned on deploying an array of GPS drifting buoys to monitor sea ice deformation at the North Pole Environmental Observatory. Unfortunately this deployment failed. Hence we had to make major revisions to our planned activities for 2009. We focused our efforts on analysis of data already at hand, and the characterization of the end-of-summer sea ice extent.

We performed a spatial scaling analysis of sea ice deformation, using ISPOL data (collected in JFY 2005) and SEDNA data (funded by NSF). Design criteria for sea ice deformation monitoring systems were identified, and an in-depth error analysis of buoy based deformation calculations was performed. These are crucial steps needed for the analysis of deformation in our joint JAMSTEC buoy deployment locations, and we provided recommendations for arctic-wide observation of sea ice deformation in a publication submitted to *J. Phys. Oceanogr*.

Jennifer Hutchings became active in the CliC sea ice working group. She is supporting organization of information regarding sea ice field campaigns through the iceplan.org web site.

Hutchings also authored a chapter in a sea ice field manual (lead editor Hajo Eicken) on the inter-relationship between fieldwork and modeling. This manual and the CliC working group was an effort toward improved coordination of sea ice field methods and data reporting.

We attended an early fall cruise in the Beaufort Sea to characterize the end-of-summer sea ice state there. Alice Orlich, an undergraduate student assistant hired part time on this project, performed an initial validation of passive microwave sea ice concentration products with in situ visual ship observations collected during Beaufort Sea cruises in the summers of 2006, 2007, 2008, and 2009.

Jennifer Hutchings and Ignatius Rigor initiated analysis of Beaufort Sea ice and the interactions between sea ice drift, deformation, and end-of-summer thickness. Two manuscripts are under preparation to be submitted to the *J. Geophys. Res.* titled “Role of ice dynamics in anomalous ice conditions in the Beaufort Sea during 2006–2008” and “Trends in Beaufort Sea Ice Pack Deformation.”
Results of 2009FY

Recommendations for design of sea ice deformation monitoring systems

Two buoy deployment campaigns (ISPOL: Austral Spring/Summer 2004–2005, Weddell Sea; and SEDNA: Boreal Winter/Spring 2007, Beaufort Sea) have provided data that identify the spatial and temporal variation in sea ice deformation. We expanded our 2008 error analysis to arbitrary buoy array design (Hutchings et al. 2010), and we identify that (a) with standard (single frequency) GPS, the minimum area deformation that can be measured over is 1km²; and (b) strain rate error is an inverse quadratic function of velocity (increasing as velocity decreases), such that the signal to noise ratio is above 1 for velocities less than 0.01 m/s.

Fig. 1. Comparison of velocity and divergence estimates using ARGOS and GPS positioning (left) Rotary power spectral density of velocity of a buoy in the Beaufort Sea estimated using ARGOS (gray) and GPS (black) positioning. Clockwise component is plotted with negative frequencies and counter-clockwise component with positive frequencies. (right) Estimate of ice pack divergence from three buoys in the Beaufort Sea using GPS (black) and ARGOS (gray) positioning.
One key finding was that ARGOS positioning is not sufficient to resolve sub-diurnal oscillations in ice pack during winter, and does not resolve part of the synoptic band (fig. 1 left). The larger position error of ARGOS introduces noise into the strain rate estimate (fig. 1 right), which results in over-estimation of opening and first year ice growth and redistribution in ridges.

![Fig. 2. Decorrelation length scale of deformation, investigated with the ISPOL buoy array.](image)

(left) Buoys were placed at 12 km spacing in a grid of triangles. Several sub-arrays within the grid, can be used to estimate sea ice deformation. Gray lines indicate the 12 km triangles, black lines are 24 km triangles where deformation was tidally cyclic (C), erratic (A), and a mixture of both (B). The shaded area represents a shear zone through the array. Buoys outside of region A were on the continental shelf and experience tidal oscillations in divergence.

(right) Correlation was estimated between time series of deformation for pairs of 12 km triangles. Note the decreasing variance in correlation coefficient as length scale between arrays increases. The mean correlation (red line in a least square fit) indicates a decorrelation length scale of around 400km. For the high correlation pairs of triangles decorrelation length scale is shorter (blue line).

We identified that variability of sea ice deformation increases as the spatial resolution of observations is increased. At the scale of spacing between linear deformation features (leads and ridges), 10 km, sea ice deformation is highly heterogeneous. Hence the investigation of localized phenomena in ocean-sea ice-atmosphere fluxes and sea ice mass balance requires localized measurements of ice pack deformation. This finding also has implications for the choice of rheological model for sea ice dynamics, where spatial scale must be taken into account when choosing a model. An ice strength parameterization that is a smoothing varying function of ice concentration and thickness is unlikely to be appropriate at 10 km resolution. The relationship also depends on ice age, floe size, and stage of melt. See Hutching et al. (2010) for more details.

We identified the need to include ice interaction in ice-ocean tide models

A comparison between deformation observed over the ISPOL array and modeled tides for the region (Padman and Kottmeier 2000) illustrates the importance of ice pack internal interaction in the ice pack force balance during earlier summer. Ice conditions within the ISPOL array encompassed two distinct regimes, driven by shear along the continental shelf break. Differences in spectral power of the tidal and inertial bands across the two regions do not mirror expected differences due to spatial...
variability of tidal deformation on the shelf break. Instead they indicate that the pack ice’s internal stress behaved anisotropically on the scale of the shear zone (>> 70 km).

**Fig. 3.** Mean spectral power of divergence, for four regions shown in Fig. 2. 99% confidence intervals are indicated with dotted lines. The gray line is a fit to red noise. Note: diurnal and semi-diurnal peaks are significant in all regions except the northeast region (region A in Fig. 2). Padman and Kottmeier’s (2000) model, which includes a free-drift representation of ice, indicated that divergence should be highest in the tidal bands along the continental shelf (region A). Our results contradict this, showing that ice interaction acts to remove divergence power from the tidal bands.

**Fig. 4.** Mean spectral power of maximum shear rate, for four regions shown in Fig 2. 99% confidence intervals are indicated with dotted lines. The gray line is a fit to red noise.

Note: There is a significant diurnal, tidally driven, peak in shear in the shear zone (region A). Unlike divergence, internal ice interaction is not damping response of the shear, along the shear zone, to tides. This indicates anisotropic behavior in the strength of the ice pack on the scale of the shear zone (>> 70km). Essentially the pack is strong perpendicular to the shear zone and weaker parallel to the shear zone.
Creation of iceplan.org
With the joint support of the Climate of the Cryosphere (CliC) sea ice working group, we developed a web site to assist in the international coordination and planning of arctic sea ice field work. See <http:iceplan.org>.

**Fig. 5.** Interactive (clickable) map of field campaigns collated for 2009 on iceplan.org. Information is provided about each campaign. The iceplan exercise is identifying gaps in sea ice coverage in the Arctic and provides a central location where researchers can go to find potential collaborators and information on measurements of interest.

Comparison of late Summer passive microwave and visual ship based ice concentration
Visual sea ice observations were recorded from the *Louis S. St. Laurent* bridge during the late summer / early autumn Beaufort Sea cruises in the four years 2006–2009. Since 2007, a camera has been mounted on the ship’s monkey island for post-cruise interpretation of ice state, and to facilitate the development of an autonomous observation system. Previous work in 2008 indicated that hourly visual observations do not correctly represent large scale (25km$^2$) in loose ice pack (see 2008 report). Hence, in 2009 we implemented a schedule of five-minute ice concentration observations in order to investigate the impact of observation interval on accuracy of large-scale ice concentration estimates.
In 2009, we were in the Beaufort during freeze-up. Hence, the ice pack could be organized into two regions: (a) a diffuse ice edge, with loose ice blown by southward winds, and (b) the refreezing central pack that was greater than 90% concentration. Improvement in ship-based ice concentration estimation was found both in the central pack and ice edge with higher frequency observation. Hence, we recommend that camera systems be employed for ship-based ice observations and autonomous algorithms developed to estimate ice concentration, ice type, and melt pond fraction, as well as integrating across images to build ice maps at satellite passive microwave resolution.

A bias between AMSR-E and SSM/I, NASA Team concentration estimates was identified. In the early refreezing ice pack, AMSR-E may slightly over-report ice concentration; SSM/I was found to under-report ice concentration in the central pack by up to 30%.

Case studies have been examined for various ice conditions encountered during the four cruises. We are discovering that the passive microwave accuracy is not always identifiable from hourly observations and varies with ice type, concentration, and stage of melt/freeze. More frequent (at least five-minute) observations are required for validation of satellite sea ice products. Hence, we require a reliable, autonomous ship-based camera system, or helicopter-based observations for this project to continue. This will require building partnerships with investigators from new groups who have expertise in visual analysis. Unfortunately, this project does not have the financial resources to support the aerial observations required. However we will partner with the Canadian Ice Service to obtain these where they perform surveys.

**Relationship between Beaufort Sea ice drift and recent ice loss**

An unusual polynya formed in the Beaufort Sea during the summer of 2006, and a new record minimum in summer sea ice extent was set in 2007. Using a combination of visual observations from cruises and estimates of sea ice concentration from the satellites (NASA Team), we show that ice dynamics during preceding years included events that preconditioned the Beaufort ice pack for the unusual patterns of opening observed in both summers.

Intrusions of first-year ice from the Chukchi Sea to the northern Beaufort, and increased poleward ice transport from the western Arctic during summer have led to
reduced replenishment of multi-year ice, older than five years, in the western Beaufort, resulting in a younger, thinner ice pack in most of the Beaufort. We find that ice younger than five years melts out completely by the end of summer south of 76°N. The 2006 polynya was bounded to the south by ice much older than five years, and formed when first-year and second-year ice melted between 76°N and the older ice to the south. We demonstrate that a recent shift in ice circulation patterns in the western Arctic preconditions the Beaufort ice pack for increased seasonal ice zone extent.

Fig. 7. (top) The area of ice with residence time less than one year, which represents mean annual ice area drift in the Transpolar Drift Stream. (bottom) Area of ice with residence time greater than five years, west of 120°E, indicating the size of the Beaufort Gyre.

The annual mean transpolar drift and Beaufort Gyre circulation (Fig. 7) are informative in understanding sea ice dynamics control on ice mass balance; however they do not provide the whole story. A large Beaufort Gyre has been related to increased ice thickness in the central Arctic and Beaufort Sea prior to year 2000. During the last decade, an enhanced Beaufort Gyre has been observed, and yet sea ice has been thinning, and export from the Arctic and Beaufort summer minimum ice extents has been declining. We find that since 2000 there has been a shift in summertime ice drift from westward to poleward drift. In 2007, this poleward drift was particularly strong and coincided with an unusually large Fram Strait export. This summer ice drift away from the Beaufort Gyre region and into the Transpolar Drift has caused decreasing ice age in the central Beaufort, where sea ice is not being re-circulated to the Chukchi Sea prior to the winter, Beaufort Gyre driven, entrainment of ice from the Chukchi Sea to the Beaufort. This change in circulation is depicted in the illustration in Fig. 8.
The younger ice pack is now melting out farther and earlier in the summer. Ice age in the southern Beaufort correlates well with end-of-summer ice extent (0.7 correlation). We find that ice younger than five years old has melted out of the Beaufort Sea each summer since 2006. As the change in ice age in the region is dynamically driven, the recent unusual summer ice extents are due, in large part, to the dynamically driven reduction in ice age in the region.

**Relationship between Beaufort Sea ice deformation and recent ice loss**

There is a trend over the last decade toward increasing pack divergence of the Beaufort Sea ice pack in late winter. This leads to 20–30% expanses of thin ice melting out earlier in summer, which may precondition the accelerated summer ice loss observed in recent years. Late winter opening in 2007 was two times greater than previously observed. Perovich et al. (2008) reported a 2 m thinning of MY ice in the Beaufort Sea in summer 2007 and hypothesized that this was caused by an increase in solar absorption in the upper ocean due to lower than normal sea ice concentration. Our results support this hypothesis and that the low ice concentration was partially driven by an anomalous opening event in the Beaufort Sea perennial ice pack in spring 2007.
Triads of buoys, provided by the International Arctic Buoy Program, encompassing the Beaufort Sea, and retaining a regular shape throughout a winter were identified. The dataset included coverage for most winters between 1992 and 2007 (Fig. 9). Within each buoy triad we estimated the ice pack divergence (Hutchings and Hibler, 2008; Hutchings et al., 2010). This divergence was used to drive a model of new ice growth and thickness redistribution.

![Percentage area of OW and FY ice](image)

![Mean FY ice thickness (m)](image)

**Fig. 10.** Observed divergence driven model of new sea ice growth and redistribution. The top panel shows the percentage area covered by open water and first-year ice inside the 12 buoy array triads. The bottom panel shows the mean thickness of first-year ice, estimated from the divergence model using Maykut and Untersteiner (1971) sea ice growth rates.

Our model results demonstrate that the summers of 2002, 2005, and 2007 were unusual in that they had large fractions of first-year ice due to enhanced deformation rates during the proceeding winter. In 2007 the first-year ice thickness at the start of summer was also half a meter less than previous years. This result indicates that solar absorption into the upper ocean may have been enhanced in 2007. Analysis of buoy array deformation in summer 2007 indicates that the Beaufort ice pack did not continue to open during that time. Hence it was the melt of an already extensive thin, young ice pack that resulted in increased solar absorption in the upper ocean in summer 2007. Our findings support the conclusion of Perovich et al. (2008), who found that unusually large melt in the region was due to enhanced solar absorption in the upper ocean. Our results provide a mechanism for this observed enhanced solar absorption.

There is a marked change in the deformation character of the ice pack in the Beaufort Sea after 1999. This is related to changes in ice pack dynamics that have led to a younger ice pack and reducing end-of-summer ice extent since 1999. Essentially, sea ice deformation in the Beaufort Sea is acting as a positive feedback in the recent loss of sea ice mass from the region.
References


Presentations
T. Kikuchi presented iceplan.org at the International Arctic Buoy Program Meeting, Tokyo Japan May 2009.


J.K. Hutchings, Where did all the ice go? Presentation to Louis S. St. Laurant crew, Beaufort Sea, October 12 2009 (seminar).

J.K. Hutchings, P. Heil and A. Roberts, Scaling properties of sea ice deformation during winter and summer, AGU Fall Meeting, San Francisco USA, December 17 2009 (poster).


Publications


Submitted

In Preparation
Research Area 1: Arctic Ocean/Sea Ice/Atmosphere
Theme 3: Storm activity and atmosphere-sea ice-ocean interaction

Introduction
Substantial changes have occurred recently in the arctic climate system. Tracking the changes reveals that they may have been greatly accelerated or may have shifted onto a fast track and interacted with lower latitudes during the most recent years. To untangle the complex suite of processes that create the arctic climate system changes and enhance arctic-global climate interactions, we hypothesize that improving understanding of intensified storm activity and its impacts on the large-scale climate system are of central importance. It has been identified that the storm track has shifted poleward and storm activity has intensified over the arctic region (e.g., Zhang et al., 2004). An increasing number of intense storms entering the Arctic intensify poleward warm and moist air transport, ocean mixing, and air-ice-sea interactions, impacting sea ice production, heat, and freshwater budgets.

Conventionally, monthly, seasonal, or annual means are used in climate studies, but this approach damps large fluctuations of sea ice mass balance changes, weakening air-ice-sea interactions, and filters transient heat and moisture transport. In particular, since the middle 1990s the Arctic/North Atlantic Oscillation (AO/NAO) has approached neutral and lost its driving connection with changes in sea ice and ocean. This motivates us to investigate amplified arctic climate changes and arctic-global climate interactions in the context of storm activity. The primary focus in this study will be on synoptic-scale storm activity and its upscaling connection with large-scale climate variability and changes, with a specific focus on extreme climate events associated with sea ice mass balance and heat and freshwater budgets. This study builds upon our previous and current JAMSTEC supported research activity and scientific achievements. It will establish physical and statistical links between integrated synoptic-scale variations and large-scale variability and change.

Objectives
1. To detect seasonal and regional changes in storm activity during the rapid climate change periods in observations and model projections.
2. To provide a schematic description of synoptic-scale variations of atmosphere, ocean, and sea ice processes under the impact of storm processes.
3. To identify underlying physical processes linked to or impacting the recently observed and future projected large-scale climate system change.
4. To quantify atmosphere and ocean heat and freshwater budgets and pathways and sea ice heat and mass balance in the context of storm activity.
5. To create a database of heat energy and water mass budgets in arctic atmosphere, ocean, and sea ice at a synoptic-scale resolution.

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Methodology

1. To employ and improve the existing storm identification and tracking algorithm for applications to reanalysis data and model simulation and projection output.
2. To augment the storm activity database and detect seasonal and regional changes of storms in the most recent rapid change episode of the arctic climate.
3. To compare several model simulation results including AFES and CFES conducted by Earth Simulator Center (JAMSTEC) in terms of change of the arctic atmospheric condition.

Activities for 2009FY

1. Improve the existing storm identification and tracking algorithm for different observational and modeling data.
2. Update the storm database and create a new database from model simulation output.
3. Explore the physics responsible for recent drastic changes in sea ice mass balance.

Results of 2009FY

Understanding formation of the Arctic Rapid Change Pattern (ARP)

Superimposed on the global-warming-forced long-term changing trends, a conspicuous rapid change episode occurred in the arctic climate system in the most recent decade. This rapid change episode is characterized coincidentally by an accelerated decline of sea ice cover, a rise in Eurasian river discharge, and a shift of the maximum surface air temperature trend from the Eurasian continent to the Arctic Ocean. These events occurred from the mid-1990s until 2006 and concluded with the extreme sea ice cover loss and the Eurasian river discharge increase in 2007 (Comiso et al., 2008; Zhang et al., 2008; Rawlins et al., 2009).

To understand these rapid changes, Zhang et al. (2008) analyzed multidisciplinary datasets and detected drastic systematic spatial changes in large-scale atmospheric circulations. There was a sudden jump from the conventional tri-polar Arctic/North Atlantic Oscillation (AO/NAO) to an unprecedented dipolar leading pattern following accelerated northeastward shifts of the AO/NAO centers of action (Fig. 1). Zhang et al. (2008) defined this radically shifted spatial pattern as the Arctic Rapid change Pattern (ARP, Fig. 1b), which represents the rapid climate change signature in Northern Hemisphere atmospheric circulation. ARP enhances arctic and lower latitude climate interactions and provides an accelerating impetus for the observed rapid changes in the arctic climate system. It played a decisive role in forming the extreme climate events of sea ice decline and hydrological intensification in 2007.
As a continuing effort in this fiscal year, we began with investigation of physical processes and mechanisms behind the poleward shift of atmospheric circulation centers of action to answer the scientific question: Why has atmospheric circulation shifted, and how was ARP formed? We conducted a statistical and dynamic diagnostic analysis by using reanalysis datasets and climate model simulations via examining internal and external forcing. In the variance analysis, our result indicates that the ARP and NAO evolve with time and the ARP took over the NAO after the mid-1990s. We made a further correlation analysis to examine scale interactions between synoptic-scale storm activity and the ARP index. The result suggests strengthened storm activity over the Eurasian Arctic and landmass may contribute to the circulation shift and the ARP formation (Figure 2). More comprehensive analysis is continuing for this study.
Fig. 2. Time evolution of variance of the ARP index (red curve) and NAO index (blue curve), and the time evolution of correlation coefficient between the storm activity over the Eurasian Arctic Ocean and costal area and the ARP index.

Sensitivity of Arctic Summer Sea Ice to Global Warming Forcing: Reducing Uncertainty in Arctic Climate Change Projections

Significantly decreasing arctic sea ice coverage is the most prominent feature and an important indicator of recently observed global-warming-forced climate changes. Although the fourth Intergovernmental Panel on Climate Change assessment report (IPCC AR4)/phase 3 of the Coupled Model Intercomparison Project (CMIP3) models unanimously project continuing, accelerating retreat of arctic sea ice coverage in the 21st century under various global warming scenarios, a large spread in the rate of sea ice area/extent decline occurred across the models and model ensemble members (e.g., Zhang and Walsh, 2006; Holland et al., 2006). In particular, the models as a whole obviously did not capture—or they considerably underestimated—the rapidly decreased sea ice cover in the latest decade and the extreme event of sea ice cover loss in summer 2007 (e.g., Stroeve et al., 2007; Comiso et al., 2008; Zhang et al., 2008).

To understand the origins of the uncertainties and to enhance the credibility of future arctic climate change assessments, we analyzed arctic summer sea ice cover to determine its sensitivity to changes in surface air temperature (SAT) in the IPCC AR4/CMIP3 models and observations for 1979–2004, when the required observational datasets are available. We used observations as a constraint to reduce uncertainties. The result suggests that the uncertainties result from the large range of sensitivities involved in the computation of sea ice mass balance by the climate models, specifically with the changes in sea ice area ranging from $0.09 \times 10^6 km^2$ to $-1.23 \times 10^6 km^2$ in response to $1.0K$ increase of air temperature. All model results as a whole are less sensitive than observations (Figure 3). The sensitivities also vary largely across ensemble members in the same model, indicating impacts of initial condition on the evolution of feedback strength with model integrations.

By observationally constraining the selected model runs by the sensitivity analysis, we captured the observed changes in sea ice area and surface air temperatures and greatly reduced their future projection uncertainties to a certain range from the currently announced one. The projected ice-free summer Arctic Ocean may occur as early as the late 2030s using a criterion of 80% sea ice area loss (Figure 4). By using the selected subset of the model runs, the arctic regional mean surface air
temperature will likely increase by $8.5^\circ C \pm 2.5^\circ C$ in winter and $3.7^\circ C \pm 0.9^\circ C$ in summer by the end of this century.

![Fig. 3. Scatter plot and linear regression of summer SIA and SAT anomalies for all 43 model runs (red) and observations (blue). The SIA and SAT anomalies are computed from 1979-2004 when observational data are available. The anomalies are relative to the climatological mean for the same time period.](image)

![Fig. 4. Sea ice area anomalies in (a) all model runs and (b) the selected subset of model runs. The anomalies are adjusted by the 1979-2004 climatologies. The red and blue lines represent the multi-model-ensemble mean and observations, respectively. The different symbol in different color represents a result from different model runs.](image)

**Synoptic View of Arctic Freshwater Budgets and Pathways**

The hydrological cycle has been intensified in the northern high latitudes in recent decades, which is strikingly evidenced by an increase of Eurasian river discharges. Although there are many impacts by various land surface processes, the atmospheric moisture transport plays a predominant role in contributing to and modulating river discharge. In the high latitudes, synoptic-scale systems such as cyclones, anticyclones and the related troughs and ridges often traveling from the west to the east, transporting and redistributing moisture generally from ocean to land and from the lower latitudes to the higher latitudes, are the fundamental weather elements.
We analyzed climatology and variability of atmospheric moisture transport associated with the weather system activity over the pan-Arctic drainage system. We divide the weather system into three categories: cyclone, anticyclone, and the transition zone between them. The results reveal that all three categories contribute to the moisture transport comparably but the values may vary in different regions (Figure 5). The seasonal variations of moisture transport by cyclones are opposite to those by anticyclones. Interannual and decadal variations of the moisture transport from all three categories correlate positively well with the total moisture transport. Moisture transport and precipitation associated with all three weather categories show an increasing trend in recent years. Influential areas of anticyclones decrease slightly, but influential areas of cyclones increase. As an integral consequence of the above weather system changes, a recently observed rapid increase in moisture transport occurred, accounting for the accelerating arctic hydrological cycle.

**Fig. 5.** Annual anomalies of the net atmospheric moisture transport into the Eurasian and North American river basins and its partitioning by cyclones, anticyclones and the flow in the transition zone between them. The values shown in the circles are the correlation coefficients between moisture transport by cyclones, anticyclones, and the flow in the transition zone with the total atmospheric circulation.

**Presentations**
Publications
Research Area 1, Theme 4: Development and application of sophisticated data-assimilation for the Arctic Ocean

Introduction

Atmospheric reanalysis products developed as a result of data assimilation into an atmospheric model play a major role in arctic system studies. These products are widely used to force sea ice, ocean and terrestrial models; to analyze the climate system’s variability; and to explain and understand the relationships among the system’s components and the causes for their change. During the previous decade, similar approaches have been developed for the ocean. Currently, there are several analyses of the ocean circulation based on the variational data assimilation technology. Meanwhile, reanalysis and reconstruction of the circulation in the ice-covered regions is a challenging task because of strong non-linearity of the ice model. Therefore, we propose to develop several integrated sets of assimilation procedures for the ice-ocean system, which would be able to provide:

- Gridded datasets that are physically consistent and optimally constrained to the observations of sea ice and ocean parameters (ocean reanalysis).
- Operational hindcast/forecast of the circulation.
- Optimal sampling strategy.

In the past two decades, the methods of oceanographic data assimilation into numerical models have undergone significant progress. Most recently, research in data assimilation has apparently trended toward studies of the ensemble-based sequential techniques (Ensemble Kalman Filtration (EnKF), Maximum Likelihood Ensemble Filter (MLEF)). These methods utilize low dimensional ensembles of model states to approximate propagation of error covariances that are vital for improvement of practical weather forecast. At the same time, the classic strong constraint 4dVar methods still remain an important tool in atmospheric and oceanic data analysis. The strong constraint methods are of particular importance in oceanography where the data coverage is sparse and observations are less accurate. With the ever growing complexity and resolution of the ocean general circulation models (OGCMs), constraining them by 4dVar methods is hampered by the following difficulties: 1) high computational cost of 4dVar optimization, 2) high maintenance cost of the adjoint and tangent linear codes, and 3) breakdown of the tangent linear approximation (TLA). In the presence of strong physical instabilities of the background state applicability of TLA is restricted to relatively short time intervals. Furthermore, the TL and adjoint codes of the community OGCMs never represent exact TL or adjoint operators, especially when model physics contains parameterized discontinuities. To resolve these difficulties we propose to develop Reduced Space 4Dvar (R4Dvar) data assimilation approach, test its performance and develop a data assimilation system based on R4Dvar.

Objectives

The objectives are:
1. To develop new data-assimilation tools:
   a. Conventional 4Dvar data assimilation systems.
   b. Ensemble Four Dimensional VARiational data assimilation (En4Dvar) and/or Maximum Likelihood Estimator Filter (MLEF).
2. To develop a data-assimilation system for the Arctic Ocean and the Bering,
Chukchi, East Siberian, and Beaufort seas.

3. To conduct a climatological reanalysis of the circulation in the Bering and Chukchi seas and in the Arctic Ocean.

4. To conduct hindcast of the circulation in the Chukchi and Beaufort seas during 2008, 2009, and 2010 and assimilation of data from Japanese, NABOS, SSS, and other cruises.

Participants
PI: Panteleev
Co-PIs: Kikuchi, Enomoto, Komori

Methodology
1. 4Dvar data assimilation into Semi-Implicit Ocean Model (SIOM).
2. Reduced space 4Dvar data assimilation (R4Dvar).
   Local Ensemble Transform Kalman Filter (LETKF).

Activities for 2009FY
1. Reconstruction of the climatological circulation in the Bering Sea:
   http://people.iarc.uaf.edu/~gleb/nprb_aleutian_passes/e_atlas_b_s/Index.htm
   http://people.iarc.uaf.edu/~gleb/nsf_arctic_reanalysis1/nsf_arctic_reanalysis1.html
3. Testing of the R4Dvar through the application to the quasi-geostrophic and simple ice models.
   http://people.iarc.uaf.edu/~gleb/ensemble_4Dvar/ensemble_4dvar.html

Results of 2009FY
Using the adjoint sensitivity and statistical correlation analyses and OSSEs, we analyzed a plan to determine optimal sites for the moorings in the Bering Strait.

Fig. 1. (Left) normalized sensitivity (correlation) map between the BST reconstructed from single-site transport observations in the Chukchi Sea (Panteleev et al., 2010a). (Right) mean reconstructed meridional velocity at the zonal section shown in the left panel by the dashed line (Panteleev et al., 2010b). Two cores of mean flow may explain the difference in correlation between Bering Strait transport and velocity at sites A3 and A2.
Fig. 2. Sensitivity maps of the transports through two sections (blue line) to velocity observations at 7.5 m.

**Adjoint sensitivity analysis of the Arctic Ocean circulation**

Adjoint sensitivity analysis and OSSEs are the perfect way to answer these questions. Figure 1 shows preliminary results of the PI’s analysis of observations along the Alaskan continental slope (SBI) and in the Beaufort Sea (BGEP). The left panel indicates that data-constrained estimates of volume transport through the section correlates well with the results of velocity observations along a relatively large part of the continental slope. In contrast, sensitivity of the transport estimate across the section in the right panel is confined to the central part of the Beaufort Gyre. Since there is no overlapping between the maps, observations in the central part of the Beaufort Sea do not provide any information about the flow through the section in the left panel. The map in the left panel, however, indicates significant correlation between the mooring sites along the Alaska Slope, and thus observations along the section in the left panel can be useful for estimating freshwater storage in the Beaufort Sea, one of the BGEP priorities.

**Optimization of the HFR radar in the Eastern Chukchi Sea**
Adjoint sensitivity analysis of the integral surface circulation with respect to HFR surface velocity observation in the eastern Chukchi Sea identify that the highest correlation “mean score” has the HF observation in site (1). HFR observations in Red Dog, site (2), have a smaller correlation with surface circulation in the region.

**Application of the R4Dvar approach to the ice model.**

Fig. 4. Results of the application of the R4Dvar approach for the ice model. Twin-data experiment. Upper row: evolution of the “true” solution of the ice model. Middle row: evolution of the first guess solution derived from data at the regular grid. Lower row: Optimized solution obtained through the R4Dvar approach. Top: evolution (decrease) of the cost function indicates good convergence of the propose approach.
Presentations


Publications

Research Area 1, Theme 5: Biogeochemical observational studies in the Arctic Ocean

Introduction

Biogeochemical data and ecosystem knowledge is limited in vast areas of the Arctic Ocean and subarctic seas. Over the last decade IARC and JAMSTEC scientist have begun to address this gap in knowledge by making observations in arctic and subarctic waters. Along with our collaborators, we have conducted biogeochemical observations in the Arctic Basins, the Siberian shelf seas (SSS: The Laptev Sea, the East Siberian Sea, and the Russian sector of the Chukchi Sea), the Chukchi Sea and the Bering Sea. Studies in the Arctic Basins and Chukchi Sea have been focused on investigating differences in the distribution of nutrients and Chlorophyll a (Chl a), and on determining how water mass dynamics affect the distribution of these parameters. Studies in SSS include estimating the spatial-temporal variability of the marine carbon cycle components, such as the transport and fate of terrestrial organic carbon in the land-shelf system, methane (CH₄) and carbon dioxide (CO₂) fluxes, as well as exploring possible linkages between chemical and physical processes that help address the transport and fate of river and Pacific-origin waters and shelf-basin interactions. Studies in the Bering Sea have investigated sources of the micronutrient iron (Fe) to surface waters, including melting sea ice and suspended particles, with particular emphasis on the outer shelf and shelf break where high productivity is observed throughout the growing season. The input and distribution of Fe and other bioactive trace metals are virtually unknown for the rest of the Arctic. There are plans to continue biogeochemical and hydrographical studies in arctic and subarctic waters in 2010 and beyond, with the main goal to quantify key biogeochemical and freshwater fluxes in the land-shelf-basin system of the Amerasian sector of the Arctic Ocean. The integration of the observations and process studies will shed light on the regional linkage of biogeochemical processes under the pan-Arctic climate system.

Objectives

1. To quantify freshwater, carbon, trace metals, and other key biogeochemical fluxes in the Arctic Ocean.
2. To integrate observations towards understanding biological activities and carbon cycling in arctic marine ecosystems.
3. To study how changes in the hydrological cycle of surrounding land and alteration of terrestrial carbon and trace metal cycles affect hydrological and biogeochemical parameters of the Arctic Ocean.

Participants

PI: Wu, Jingfeng (IARC/UAF)*
Co-PI: Aguilar-Islas, Ana M. (IARC/UAF)
Kikuchi, Takashi (JAMSTEC)
Nishino, Shigeto (JAMSTEC)
Semiletov, Igor (IARC/UAF)
Shakhova, Natalia (IARC/UAF)

* Note: The PI was changed from Jingfeng Wu to Ana M. Aguilar-Islas after Dr. Wu left IARC/UAF
Methodology

- Oceanographic observations of Arctic Basins onboard the R/V Mirai during September/October 2009.
- Oceanographic and atmospheric observations in the SSS during July 2009.
- Collection of ice cores and snow samples using trace metal clean protocols.
- Trace metal observations in coastal Alaskan arctic rivers.

Activities for 2009FY

- **R/V Mirai Arctic cruise (September/October 2009).**
  Observation during the R/V Mirai (MR09-03) cruise were made to clarify the biogeochemical response related to the rapid reduction of Arctic summer sea ice.
- Cruises to the SSS onboard Russian vessels: R/V TB-0012/SSS and Kapitan Dranytsin.
  Observations made to estimate the spatial-temporal variability of the marine carbon cycle components, such as the transport and fate of terrestrial organic carbon in the land-shelf system, and the fluxes of CH₄ and CO₂.
- Field trip to Barrow, Alaska (March 2009).
  Ice cores and snow samples were collected at two fast ice stations near Barrow, Alaska, for their use in laboratory experiments addressing trace metal cycling in sea ice.
- Field trips to Prudhoe Bay, Alaska (May and July 2009).
  River samples were collected from the Kuparuk and Sagavarnirktok rivers during high flow (May) and low flow (July) seasons to investigate the effect of river flow on the delivery of trace metals to the coastal Arctic Ocean.
- Ice camp on Granite Harbour, Antarctica (November/December 2009).
  Methods for growing sea ice in a trace-metal clean fashion were developed and tested.
- Analysis of data to detect biogeochemical changes over the Siberian shelves, slopes, and the Arctic basins.
- Analysis of data to improve understanding of bio-available Fe sources in the Bering Sea.

Results of 2009FY

**R/V Mirai Arctic cruise in 2009**

In late summer 2009 (7 September–15 October), the R/V Mirai conducted hydrographic surveys in the open waters of the Chukchi Sea and Canada Basin, and was named a Multi-disciplinary Observation Cruise for the Arctic Ocean (Cruise code: MR09-03; Chief Scientist: Dr. Takashi Kikuchi, JAMSTEC). The focus of the surveys was:

- a. To quantify on-going changes in ocean, atmosphere, and ecosystem, which are related to the recent arctic warming and sea ice reduction.
- b. To clarify important processes and interactions among atmosphere, ocean, and ecosystem behind changes of the Arctic Ocean.
- c. To collect data for understanding the effects of Arctic Ocean changes on the global climate.

Some surveys were coordinated with IARC scientists based on the IA for JFY2009 under the CA between JAMSTEC and UAF/IARC. This coordination promotes the study on the phytoplankton activities in the Arctic Ocean, especially the role of melting sea ice in providing the micronutrient Fe to surface waters, and its
potential influence on the phytoplankton bloom. As a first step, we examined the distribution and size fractionation of Chl-a, and carbon and nitrogen (nitrate and ammonium) uptake rates by phytoplankton in this cruise. This was the first time carbon and nitrogen uptake rates were measured on board the R/V Mirai Arctic cruises, adding to the few data reported for the Arctic Ocean. We are planning to examine the distribution of Fe in the next R/V Mirai Arctic cruise in 2010 (MR10-05).

A conductivity-temperature-depth system (CTD; Sea-Bird Electronics Inc., SBE9plus) and a Carousel water sampling system with 36 Niskin bottles (12 L) were used for the hydrographic surveys. Sensors attached to the CTD system measured pressure, temperature, salinity, oxygen, fluorescence, and PAR (photosynthetically active radiation). Seawater samples were collected for analyses of salinity, oxygen, nitrate, nitrite, phosphate, silicate, ammonium, dissolved inorganic carbon (DIC), total alkalinity, δ18O, Chl-a (total Chl-a, >10µm Chl-a, 5-10µm Chl-a, 2-5µm Chl-a, 0.7-2µm Chl-a), as well as carbon and nitrogen (ammonium and nitrate) uptake rates by phytoplankton. Other biological and chemical parameters, e.g., bacteria, POM, DOM, phytoplankton species, radio carbons, etc., were also measured by Japanese scientists. Figure 1 shows the hydrographic stations of the cruise. The numbers of CTD and water sampling casts in this cruise were 100 and 65, respectively.

A drastic change was found in the Chl-a distribution. Our size fractionated Chl-a data from the R/V Mirai Arctic cruise in 2002 (Figure 2a) indicated that large-size cells (>10µm Chl-a) were found in the Canada Basin in 2002, but not in 2009 (Figures 2b and 3b). In addition, the nutricline deepened in 2009 compared with that in 2002 (Figures 2c and 3c). The deepening of the nutricline likely resulted from sea-ice melt. The fraction of sea-ice melt is calculated from salinity and total alkalinity (Yamamoto-Kawai et al., 2005), and our observations indicate a definite increase from 2002 to 2009 (Figures 2d and 3d). Therefore, the increase in sea-ice melt deepened the nutricline and prevented the nutrient supply from deeper layers, resulting in the disappearance of large-size phytoplankton. The large-size phytoplankton plays an important role in the biological pump, because its detritus effectively transports organic carbons to deeper layers. The disappearance of large-size phytoplankton in the Canada Basin in 2009 implies a reduction of the biological pump. This result is opposite to the observed fact that increase in sea-ice melt enhances the biological pump in the Siberian Arctic Ocean, due to melt waters improving the light condition for photosynthesis (Nishino et al., 2009).

The enhancement/reduction of the biological pump accompanied by sea-ice reduction is related to the ocean circulation. The anticyclonic ocean circulation (Beaufort Gyre) occupies the central Canada Basin, where the surface fresh water is accumulated by the convergence of Ekman transport. In this region, the nutricline deepens due to the recent sea-ice melt, resulting in a reduced biological pump.
However, at the limb of the Beaufort Gyre, for example, in the Siberian Arctic Ocean, the nutricline is shallow. In this region, the improvement of light availability due to the sea-ice melt enhances the biological pump.

![Figure 2](image1.png)  
**Fig. 2.** (a) Stations of the R/V Mirai Arctic cruise in 2002 for the illustration of vertical sections of (b) size fractionated chlorophyll a [μ g/L] >10 μ m, (c) nitrate [μ mol/kg], (d) fraction of sea-ice melt.

![Figure 3](image2.png)  
**Fig. 3.** (a) Stations of the R/V Mirai Arctic cruise in 2009 for the illustration of vertical sections of (b) size fractionated chlorophyll a [μ g/L] >10 μ m, (c) nitrate [μ mol/kg], (d) fraction of sea-ice melt.

![Figure 4](image3.png)  
**Fig. 4.** Dynamic Height [dyn m] at 100 m relative to 250 m (dashed lines) and N* [μ mol/kg] at 100 m (gray scale) in (a) 2002 and (b) 2009. Data of 2002 are obtained from the R/V Mirai Arctic cruise and Chukchi Borderland cruise (Woodgate *et al.*, 2005), and data of 2009 are obtained from the R/V Mirai cruise. Along thick lines in (a) and (b), vertical sections of Figures 3 and 4 are illustrated, respectively.
A change in nutrient pathways related to the ocean circulation would also influence the phytoplankton distribution and the biological pump. Nutrient-rich shelf water is characterized by low $N^*$, where $N^*$ is defined as $N^* = 0.87 ([\text{NO}_3^-] - 16[\text{PO}_4^{3-}] + 2.9)$ (µmol/kg). Low $N^*$ shelf water seems to spread into the central Canada Basin via the anticyclonic circulation in 2002 (Figure 4a). On the other hand, in the case of 2009, the accumulation of fresh water in the Canada Basin also deepens the pycnocline and causes a frontal structure of isopycnal surfaces between the shelf and basin. As a result, a strong westward flow is formed over the shelf slope (Figure 4b). The strong westward flow prevents the spreading of nutrient-rich shelf water into the Canada Basin. This blocking of shelf water spreading inhibits the growth of phytoplankton and reduces the biological pump in the Canada Basin.

As described above, the ocean circulation provides a control on the magnitude of the biological pump. The organic carbon flux through the biological pump could be balanced by new production (defined as primary production resulting from external nitrogen sources) with nitrate mainly from nutrient-rich deeper layers. We calculated new production from carbon and nitrogen (nitrate and ammonium) uptake rates obtained from the cruise in 2009 (Figure 5). The distribution of new production is consistent with what is expected from ocean circulation. The new production is enhanced not only in the shelf region, but also in the western limb of the Beaufort Gyre, i.e., the Siberian Arctic Ocean. This strongly supports the conclusion that the biological pump is large in this area.

**Combined analysis of data from JAMSTEC and IARC**

To detect biogeochemical changes over the Siberian shelves, slopes, and the arctic basins, we analyzed the *R/V Mirai* data combined with the data from Nansen and Amundsen Basins Observatory System (NABOS) project led by IARC (Polyakov and Timokhov, 2008) and the Hydrochemical Atlas of the Arctic Ocean created by IARC (Colony and Timokhov, 2001). Part of the analysis is published by Nishino et al. (2009).

Nishino et al. (2009) compared silicate profiles obtained from the *R/V Mirai* Arctic cruise in 2004 and the Arctic Ocean Section in 1994 (AOS94; Wheeler, 1997) at almost the same location over the shelf slope adjacent to the western Canada Basin off eastern Siberia. The station was covered by sea ice in 1994 (Figure 6a) but was in open water in 2004 (Figure 6b). The surface silicate concentration of 2004 was lower than that of 1994 (Figure 6c). The lower concentration in 2004 probably reflected biological uptake of silicate in the absence of sea ice in summer. At deeper depths, the silicate concentration of 2004 was higher than that of 1994, suggesting an increase in silicate regeneration caused by the decomposition of opal-containing organisms (e.g., diatom) that were transported from the surface. From these results, we can infer that the biological pump was enhanced by the sea-ice loss which improved the light condition for photosynthesis in the water column (Figure 7).

In a region farther west, Russian vessels have conducted hydrographic surveys as part of the NABOS project led by IARC. Polyakov and Timokhov (2008) reported that during the NABOS cruise in 2008, relatively high surface silicate concentrations
(10–15 µmol/L) were observed over the shelf slope of the East Siberian Sea near the Lomonosov Ridge, but silicate concentrations below the surface were constantly low (<8 µmol/L). This region was covered by sea ice in summer 2008. Therefore, water column biological production would be inhibited, and the silicate maximum would not form in deeper layers.

Although the Siberian side of the Arctic Ocean is covered by sea ice, even in summer, the relatively high surface nutrient concentrations, as reported from the NABOS cruise, imply the possibility of a drastic increase in biological productivity if the sea ice disappears. In this region, Russian rivers may influence the surface nutrient concentrations. To examine the contribution of Russian river water to the surface nutrient distribution, the amount of silicate in the 10 m surface layer was investigated using data obtained from the Hydrochemical Atlas of the Arctic Ocean (Colony and Timokhov, 2001), and is shown in Figure 8. Extremely high silicate contents were found over the Siberian shelves, reflecting the influence of Russian rivers (Vetrov and Romankevich, 2004; Semiletov et al., 2005). This high-silicate water seems to spread along the Lomonosov Ridge and into the central Arctic Ocean. Although the Pacific water also transports a large amount of nutrients, this water is subducted below the euphotic zone in the Canada Basin (Nishino et al., 2008). In contrast, because of its low density, the Russian river water occupies the surface layer and nutrients originating from these rivers would be
effectively supplied to the euphotic zone. Therefore, the Lomonosov Ridge, along which Russian river water may contribute to increased concentrations of surface nutrients, is a key area for the future study of changes in biogeochemical cycles accompanying sea-ice reduction. Such changes in the Arctic Ocean may also influence global biogeochemical cycles. For example, increased biological production in the Arctic Ocean would reduce the nutrient concentrations of water outflowing through the Canadian Archipelago and Fram Strait, and therefore might reduce productivity in the subarctic Atlantic Ocean.

**Siberian Shelf Seas**

The Arctic Ocean is surrounded by offshore and onshore permafrost which is being degraded at increasing rates under warming conditions. This warming is most pronounced in the East Siberian part of the Arctic, where surface air temperature increased during the 2000-2005 by about 5°C compared to 20th century temperature patterns (Fig. 9). The East Siberian Arctic shelf is the world’s largest continental shelf and also the most understudied part of the Arctic Ocean. Composed of the Laptev Sea, the East Siberian Sea, and the Russian section of the Chukchi Sea, this area is characterized by discharge from the tundra that travels through the Lena, Indigirka, and Kolyma rivers; coastal erosion; CH₄ seeps from sub-sea permafrost reservoirs; and the formation of water masses that spread throughout the Arctic Ocean. This region is also of particular interest for its carbon-climate couplings.

Data collected during the last 10 years in the SSS cruises (Fig. 10) were analyzed. We have found that eroded terrestrial carbon (characterized by light Corg-δ¹³C ~ -27 ‰) is transported over the entire East Siberian Arctic Shelf and is the dominant source of carbon. This is illustrated in Figure 11. Using air and dissolved methane data, sub-sediment profiling and multi-beam sonar deployed in the methane seepage field (Fig. 12), we have documented again an extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf (Shakhova et al., 2010ab, 2009abc). The annual outgassing from the shallow East Siberian Arctic Shelf of 7.98 Tg C-C₄ is of the same magnitude as existing estimates of total methane emissions of the entire world ocean (Shakhova et al., 2010b). We numerically modeled subsea permafrost dynamics in the Dmitry Laptev Strait of the East Siberian Sea since the end of the last glacial period. Modeling results were tested by drilling data showing mechanisms for
formation of taliks as the pathways for geological methane release in some areas of the East Siberian Arctic Shelf (Shakhova et al., 2009d).

Results were presented at the EGU (in total 12 reports, some are listed below) and other meetings and were published in 12 peer-reviewed journals, and in the WWF Climate Feedback Report, which was widely discussed at the WMO Meeting in Geneva, Switzerland (October 2009), and the UN Meeting in Oslo (December 2009).

**Sources of iron in the Bering Sea**

The Bering Sea shelf exhibits an offshore gradient of increasing primary production with the highest productivity at the shelf break, an area known as the Green Belt (Springer et al., 1996). Offshore of the Green Belt, the surface waters of the deep basin exhibit iron-limited, high-nutrient low-chlorophyll (HNLC) conditions (Leblanc et al., 2005; Aguilar-Islas et al., 2007). Our previous studies have shown that during spring, melting sea ice provides a source of Fe which can be biologically important at the outer shelf/shelf break where nutrient concentrations are high and sedimentary Fe input is minimal (Aguilar-Islas et al. 2008). This result has implications for Bering Sea productivity, given expected future sea ice reduction. During summer the Bering Sea is free of sea ice, with alternate sources of Fe to surface waters. Leachable Fe from suspended particles is a potential source of biologically available Fe. We have recently analyzed particulate Fe data collected in
the Bering Sea during August, 2003 (R/V Kilomoana, Bruland, 2003) (Figure 13a) and have found that subsurface waters in the Bering Sea have unusually high concentrations of leachable particulate Fe (81% on average) (Figure 13c) when compared to other productive areas (22% on average) (Hurst et al., in press). In this paper we suggest that the high concentration of leachable particulate Fe in bottom waters of the Bering Sea shelf results from the flux of reduced (dissolved) Fe from the surface sediment layer into the water column, and its subsequent oxidation/precipitation in the well-oxygenated bottom waters. Elevated leachable particulate Fe was also observed in surface waters near the Pribilof Islands where enhanced vertical mixing occurs. Summer storms can also mix subsurface waters into the surface. Mesoscale eddies at the shelf break (Kinney et al., 2009) and the shelf break front can serve as a mechanism for transporting waters enriched with leachable particulate Fe to the Green Belt. Future research is needed to address the biological availability of leachable particulate Fe and to understand its influence on the productivity of the Bering Sea.

Iron cycling in sea ice

As stated above, our research indicates that sea ice-derived iron likely plays an important role in controlling the dynamics of the spring phytoplankton bloom in seasonal ice zones characterized by high macronutrients and low iron concentrations such as the outer shelf of Bering Sea. Iron is also an essential micronutrient for sea ice algae. In seasonally ice-covered waters, 4% to 26% of the total primary production is derived from sea-ice algae (Legendre et al., 1992), and in perennially ice-covered waters this fraction can represent more than 50% (Gosselin et al., 1997). Despite its potential importance, very limited knowledge exists on the biogeochemical cycling of Fe in sea ice and the impact of anticipated climatic changes. The limited sea ice Fe...
data available indicate that dissolved Fe concentrations are elevated in sea ice relative to the underlying seawater (Grotti et al., 2005; Lannuzel et al., 2007; Aguilar-Islas et al., 2008), suggesting that micronutrient-replete microenvironments possibly exist within the sea ice matrix. Possible sources contributing to the trace metal content of sea ice include entrainment of dissolved and particulate material during formation, subsequent atmospheric deposition and accumulation of dissolved constituents from the underlying water column. The relative importance of these sources has not been determined, but likely varies with geographical location. Differences in the ratio of Fe to macronutrients and other trace metals in sea ice and how these ratios might affect sea ice productivity and community composition have not been established. In addition, limited information exists regarding the physical and chemical speciation of trace metals in sea ice, and how this speciation affects the residence time of sea ice-derived trace metals in surface waters upon melting.

To address some of these unknowns, we are developing trace metal clean methods for investigating sea ice Fe cycling in situ and in the lab. During our recent ice camp in Granite Harbour, Antarctica, we tested our new field methodology and successfully grew sea ice in situ in a trace metal clean fashion. Table 1 lists Fe concentrations from replicates grown in-situ over an 8-day period.

Table 1. Dissolved (\(< 0.2 \mu m\)) Fe concentrations in sea ice replicates

<table>
<thead>
<tr>
<th>Replicates day 2</th>
<th>Average Concentration</th>
<th>Notes</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replicates day 4</td>
<td>2.84 ± 0.58 nM Fe</td>
<td>Sea water 2.79 nM Fe. Added</td>
<td></td>
</tr>
<tr>
<td>Replicates day 6</td>
<td>6.37 ± 1.0 nM Fe</td>
<td>Fe from surface snow falling</td>
<td></td>
</tr>
<tr>
<td>Replicates day 8</td>
<td>3.86 ± 0.79 nM Fe</td>
<td>into growing tubes</td>
<td></td>
</tr>
</tbody>
</table>

**River input of trace metals into the coastal Arctic**

The Arctic Ocean is highly influenced by river input. A remarkable feature of most arctic rivers is their flow regime, with 40% to 80% of their annual flow occurring during the spring flooding events (Gordee et al. 1996). During the high flow season, even small rivers can intrude tens of kilometers offshore, due to the seasonal cover of land-fast ice which inhibits mixing. Previous studies have suggested that during flooding events the concentration of trace metals tends to be significantly higher than for the rest of the year for both small and large rivers (Rember and Trefry, 2004; Holemann et al., 2005). Despite the importance of trace metals in
aquatic ecosystems (including fish, marine mammals and humans engaged in subsistence hunting and fishing), few trace metal studies have been carried out in water reservoirs within the Alaskan Arctic. To address objective #3, we have sampled the upper and lower Kuparuk (a tundra river), and the lower Sagavanirktok (a mountain river) during a late spring flooding event (26–28 May, 2009) and during low flow (28–30 July, 2009). Chemical analysis is in progress. An objective of this study is to determine how the flow regime affects the relative size partitioning and the absolute concentration of trace metals flowing into the coastal Arctic.

**Presentations**


**Workshops**


(ttp://www.ldeo.columbia.edu/res/pi/geotraces/PW2009_ArcticCruise.html)

**Publications**


Nishino, S., K. Shimada, M. Itoh and S. Chiba (2009), Vertical double silicate maxima in the sea-ice reduction region of the western Arctic Ocean: Implications...


**References**


Research Area 2: Terrestrial Processes and Variation
Theme 6: Ecosystem and their variability
6-1: Vegetation mapping by satellite remote sensing accompanied with ground-based forest survey in Alaska (PI: Suzuki, Co-Is: Kim, Ishii, Li, Nicoll)

Introduction
Vegetation, the main component of the global ecosystem, has a function to drive the carbon cycle between the atmosphere and the land surface through photosynthesis. Since the carbon cycle controls the atmospheric CO2 concentration, the most essential greenhouse gas, the investigation of vegetation photosynthesis is important for climate change studies. Moreover, since vegetation has a function to store the carbon in its body as biomass, the monitoring of vegetation biomass is significant for the study on food, log, and fuel resources in addition to the carbon cycle. This theme focuses on these two vegetation functions, photosynthesis (i.e. productivity) and carbon stock as the biomass by the satellite remote sensing and field surveys over the boreal forest in Alaska.

Objectives
Forest above-ground biomass mapping by ALOS/PALSAR
The first objective of this theme is to map the forest above-ground biomass (FAGB) distribution of boreal forests in Alaska. The primary input to the mapping effort is the measurement of the sensor “Phased Array type L-band Synthetic Aperture Radar (PALSAR)” of the satellite “Advanced Land Observing Satellite (ALOS).” In the summer of 2007, the forest survey was executed to acquire the ground truth FAGB at 29 forests along the transect in the ecotone from Fairbanks to the Brooks Range (Fig. 1). Based on these ground truth FAGBs, an algorithm to estimate the FAGB by ALOS/PALSAR was developed in 2008FY. In 2009FY, we made the first trial to map the FAGB distribution along the transect by ALOS/PALSAR.

Fig. 1. Distribution of 29 forest sites (circle) and no-forest sites (square) that were targeted for the field survey of the forest above ground biomass (FAGB) in northern Alaska.
The measurement of ALOS/PALSAR is contaminated by the terrain effect, and therefore the estimated FAGB is uncertain. The other objective in 2009FY was to develop a methodology to reduce the contamination due to the terrain effect.

(1) Study of Forest Leaf Area Index (LAI) and phenology

For the analysis of vegetation productivity, this theme focuses the spatio-temporal variability of the forest Leaf Area Index (LAI), the total area of green leaves in a unit land area, as the proxy of photosynthetic potential. The annual productivity of the vegetation can be estimated based on the LAI and the phenology that defines the growing season of the vegetation. We try to estimate the LAI and phenology by satellite remote sensing images for the modeling of the ecosystem.

The objective in 2009FY was to find the appropriate forest site for surveying the LAI and the phenology in relation to the satellite remote sensing, and to plan the facility/equipment and the schedule for the forest survey.

Participants
PI: Rikie Suzuki (RIGC-JAMSTEC)
Co-Investigators: Yongwon Kim (IARC-UAF), Reiichiro Ishii (RIGC-JAMSTEC), Jeremy Nicoll (GI-UAF), Shin Nagai (RIGC-JAMSTEC)

Methodology
(1) Forest above-ground biomass mapping by ALOS/PALSAR

As aforementioned in the objective section, 29 forests in the transect (Fig. 1) were targeted for the FAGB survey in the summer of 2007. These forests satisfied the following conditions: they were accessible from the road, had almost no slope, and were wider than 100 m × 100 m. As introduced in Fig. 2, the major tree species is
black spruce (*Picea mariana*) and white spruce (*Picea glauca*). Birch (*Betula neoalaskana*) occurs in some forests but is relatively rare. The following surveys were carried out in July, 2007.

- FAGB at 29 forests (FAGB 2 or 3 points were measured and averaged for each forest) by Bitterlich Angle Count Sampling method and Sampled-tree Measuring (BACS-STM) method and allometry equations.
- The geo-position of 16 non-forest areas for zero FAGB.

These ground truth FAGBs are compared to the Normalized Radar Cross Section (NRCS) of ALOS/PALSAR, and then, the FAGB estimation algorithm was constructed according to the linear regression line (Fig. 3).

(2) Study of Forest Leaf Area Index (LAI) and phenology

This theme aims to develop an algorithm to estimate the LAI based on satellite image by applying the 3D forest radiative transfer model called “FLiES” considering the Bi-directional Reflectance Factor (BRF) of the forest. The ground truth data of BRF have to be the spectral reflectance of the forest from various viewing angles above the forest crown at various diurnal and seasonal timings. For this observation, a tower higher than the forest canopy is required. The FLiES will be applied for the observation of the sensor “Second-generation GLI (SGLI)” of the satellite “Global Change Observation Mission (GCOM),” and will make an attempt to estimate accurately the geographical distribution of the forest LAI.

![Fig. 3. The relationship between the forest above-ground biomass (FAGB) (dry matter) and the NRCS (HV mode) of ALOS/PALSAR.](image)

The forest phenology is observed by interval cameras. The RGB digital number of the camera image will be related to the RGB image of Moderate-resolution Imaging Spectroradiometer (MODIS) of Terra/Aqua, and map the phenological event of the boreal forest over Alaska. The estimated LAI and phenological feature will be applied to the modeling of the vegetation productivity and the mapping of its geographical distribution.
Activities for 2009FY

(1) Forest above-ground biomass mapping by ALOS/PALSAR.

The ground truth FAGBs at 29 forests were compared with NRCS (HV mode) of ALOS/PALSAR. Also the NRCSs at the 16 non-forest areas were incorporated as the zero FAGB. Based on the linear regression line between FAGB and NRCS (Fig. 3), the FAGB estimation algorithm for ALOS/PALSAR was constructed, and the estimated FAGB along the transect was mapped (Fig. 4).

Fig. 4. Distribution of the NRCS of ALOS/PALSAR in HV mode in summer of 2007 (left), and the distribution of the estimated forest above-ground biomass (FAGB) (Mg/ha) (right). The region with negative FAGB estimation is set at zero.

(2) Study of Forest Leaf Area Index (LAI) and phenology.

A tower, from which the BRF can be observed, is required. In 2009FY, we searched a boreal forest that was typical in Alaska and appropriate for the implementation of the tower, and consequently found such a forest in the supersite of the Poker Flat Research Range (PFRR) of the University of Alaska Fairbanks (Fig. 5). The availability of the spectro-radiometer (FieldSpec FR), which will be used for the spectral reflectance observation of the forest tower, was checked. The interval camera, which will be used for the observation of the forest phenology, was purchased.
Results of 2009FY

(1) Forest above-ground biomass mapping by ALOS/PALSAR.

Fig. 4 demonstrates the FAGB distribution that was estimated by the relationship shown in Fig. 3. Negative FAGB estimations were set at zero. Generally, there is a south to north gradient in FAGB that reflects the vegetation biomass gradient from the southern forest-rich region to the northern forest-sparse region in the ecotone. The FAGB in some regions in the southern part reaches 100 Mg/ha.

The FAGB in northern mountainous region indicates a complicated granule pattern. This is an estimation error of FAGB induced by the terrain effect. An attempt to reduce this error was conducted by evaluating the degree and azimuth of each slope by using the digital elevation model of Alaska.

(2) Study of Forest Leaf Area Index (LAI) and phenology.

Preparations for the forest survey in PFRR began in 2009FY. In 2010FY, the forest tower will be constructed and observations of forest spectral reflectance and phenology will begin.

Presentations


**Publications**


Theme 7 State of snow and ice and variability
7-1: Surface/Subsurface Hydro-thermal Regimes in the frost region

Introduction
Frozen ground and snow make critical environmental conditions in the terrestrial cryosphere, in terms of the cycle of energy, water, and materials (carbon, nitrogen, etc.) between the atmosphere, land, and ocean, as well as the local vegetations. The importance of those processes in R/GCM (Regional or Global climate models) has recently been recognized (e.g., Saito 2008a, b). Utilization of appropriate values of the physical property of soil and snow (including its change in time and place) are necessary for realistic simulations (e.g., thermal conductivity, permeability, etc.). However, only very crude values are usually used without careful examination supported by observations (e.g., application of a globally and annually constant value). This needs to be examined in cooperation with the observations.

Another important aspect is to bridge the plot/local and the large scales (e.g., from the plot-scale ground-based observations to the large-scale satellite observation and/or modeling outputs). This project aims to evaluate the climatic/latitudinal gradient of the values of the primary physical properties and the vertical profiles that are currently used in the large-scale models.

Objectives
This sub-theme is aimed at improving the capability of the freezing/thawing processes in the climate modeling, as well as the understanding of the influence and feedbacks of such processes to the large-scale climate. The direct objective is to measure, evaluate, and analyze the climatic/latitudinal gradients of:

a) sub-surface properties (vertical profile of soil type, and thermal and hydraulic properties)
b) snow properties, at the different climatic zones in Alaska (from tundra to taiga, from continental to coastal/maritime climate zones), to be used for validation, calibration and refinement of the physical terrestrial model.

The snow property measurement (b) is conducted in close liaison with the project done within the framework of the IARC-JAXA collaboration.

Participants
PI: Kazuyuki Saito
Co-PI: Konosuke Sugiura
Field observations; measurement, analysis, maintenance
Kazuyuki Saito (IARC/UAF, RIGC/JAMSTEC)*
Jessie Cherry (IARC/UAF, WERC/UAF)*
Jessie Cable (IARC/UAF)
Yongwon Kim (IARC/UAF)
Konosuke Sugiura (JAMSTEC)*
Mamoru Ishikawa (Hokkaido U)*
Atsushi Sato (NIED), Takeshi Sato (NIED)*
(*participated in the work conducted in this FY)

Data and Modeling comparison
Yoshihiro Iijima (JAMSTEC) for data in Russia and/or Mongol
Hotaek Park (JAMSTEC)
Possible Japanese collaborator in the field measurement in Japan for climatic/latitudinal comparison
Ken Motoya (Akita U.)

The following people gave advice and/or support in conducting activities in FY 2009, although not listed as participants:
Kenji Yoshikawa (WERC/UAF) for observational settings and equipment in Valdez,
Bob Busey (WERC/UAF, IARC/UAF) for observational settings and equipment for the UAF and Kougarok sites, and Koichiro Harada (Miyagi University) for location hunting, observational settings, and measurement in Kougarok.

Methodology
1. Continuous measurement: meteorological variables (AWS), soil temperature, soil moisture. Collaborative management and maintenance with IARC/UAF and NIED.
2. Ad hoc sampling and analyses of soil materials: porosity, thermal property, hydraulic property, organic contents at UAF facilities (WERC, GI, IARC) and Japanese facilities.
3. Numerical land process scheme that runs off-line (stand-alone) and on-line (coupled with an atmospheric GCM. MIROC [K-1 model developers, 2004] with a land scheme model MATSIRO (Takata et al. 2003; Saito 2008b)).

Activities of 2009 FY
Planned activities for 2009 FY included selecting and determining observational sites, observation/laboratory plans, and doing a preliminary survey (at UAF).

Field activities conducted in FY2009 were:
2. September 4–14: Barrow, CPCRW, PFRR (planned with Dr. Ishikawa for location inspection for boreholes and installment of new measurement equipment, but cancelled for his conflict of schedules, and postponed to 2010 FY).
3. August 19–26: Location inspection and ad hoc measurement of soil thermal properties in the tundra environment (with and without tundra fire experiences), Seward Peninsula, Kougarok, Quartz Creek.
5. December 25 to February 4: Installment of soil temperature measurement and measurement of soil thermal properties (minerals and surface organic layers) in the Antarctic Peninsula region.

Results of 2009 FY
Available existing observational sites
After the search for available existing data and negotiations for use, the following groups/sites have been included in the project:
1. Caribou Poker Creek Research Watershed (collaboration with the NIED observation).
2. Kougarok, Seward Peninsula (utilization of ATLAS Project products; collaboration with Jessie Cherry).
Selection of the sites and installment of equipment

During FY 2008–2009, either the ad hoc measurement of vertical profile of the soil physical property (thermal conductivity, heat capacity), temperature, and soil moisture or installment of the measurement equipment was conducted at the following sites:

a) UAF forest site (Smith lake)
   Preliminary continuous measurement of thermal conductivity, temperature of the near-surface atmosphere and ground at the 10cm depth; ad hoc survey of thermal properties of soil with KD2 Pro (Fig. 1a).

b) Quartz Creek, Kougarok, Seward Peninsula
   Ad hoc survey of thermal properties, temperature, and soil moisture in several pitches. See also “Role of Snow in Land-Atmosphere Interactions.”

c) Valdez
   At a site representing a high amount of snow fall and accumulation in a non-permafrost area, the instrument to measure the hourly temperature profile at the snow-ground interface and 10cm-deep soil were installed in the woods near the airport at the outskirts of Valdez, AK, on November 13, 2009 (Fig. 1b). Due to the spatial limitations available to set up the pole, only one PVC pole of 3.5 m was used at the Valdez site with sensors attached to the different designed heights and depths.

d) Antarctica (King George Island, James Ross Island)
   Four different sites were chosen in areas at the tip of the Antarctic Peninsula: two on King George Island, the western side of the peninsula, and the other two on James Ross Island, the eastern side of the peninsula (Figures 1c–1f). Both sides of the peninsula show contrasting characteristics of the climatic conditions. The western side is warmer and wetter with a larger amount of precipitation (both in solid and liquid states), while the eastern side shows cooler and drier climate resulting from higher sea ice concentrations in the eastern side of the peninsula (Weddell Sea).

The geographical and methodological information is summarized in Table 1. The obtained results from those observations will be analyzed to characterize the seasonal change in the soil temperature at those different climatic areas, as well as to compare the thermal properties deduced by the change in amplitude and phase of the temperature series at the upper soil layer.
Table 1. Summary of the observational locations.

<table>
<thead>
<tr>
<th>Site</th>
<th>Place</th>
<th>Lat</th>
<th>Lon</th>
<th>Height/depth of sensors (cm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz Creek</td>
<td>Seward Peninsula, AK</td>
<td>N65°25'42.0&quot;</td>
<td>W164°38'36.6&quot;</td>
<td>approximately 0-1m in 2 cm increments</td>
</tr>
<tr>
<td>Valdez</td>
<td>Valdez, AK</td>
<td>N61°08'05.6&quot;</td>
<td>W146°12'46.6&quot;</td>
<td>-20, 0, and 270</td>
</tr>
<tr>
<td>Vegetated Moraine</td>
<td>King George Isl., Antarc.</td>
<td>S62°14'41.1&quot;</td>
<td>W58°39'13.4&quot;</td>
<td>-100, -10, 0, and 200</td>
</tr>
<tr>
<td>Glacifluvial Plain</td>
<td>King George Isl., Antarc.</td>
<td>S62°14'19.4&quot;</td>
<td>W58°38'38.0&quot;</td>
<td>0, 10, 25, and 100</td>
</tr>
<tr>
<td>Sta. Marta Plain</td>
<td>James Ross Isl., Antarc.</td>
<td>S63°54'51.1&quot;</td>
<td>W57°51'26.8&quot;</td>
<td>-10, 0, 15, and 80</td>
</tr>
<tr>
<td>Rink Alto</td>
<td>James Ross Isl., Antarc.</td>
<td>S63°54'12.3&quot;</td>
<td>W58°12'23.1&quot;</td>
<td>-10, 0, 10, and 40</td>
</tr>
</tbody>
</table>

*: Negative numbers denote depth in the soil from the surface.
Fig. 1. Installed measurement equipments for snow temperature profile. a) UAF forest (Smith Lake), b) Valdez, c) Vegetated Moraine (King George Island, the Antarctica), d) Glacifluvial Plain (King George Island), e) Santa Marta Plain (James Ross Island, the Antarctica), and f) Rink Alto (James Ross Island).

**Preliminary analyses for retrieving soil thermal properties**

*Inference by amplitude dumping ratio and phase shift*

The temperature time series at different depths in soil or snow is analyzed based on the assumption of the ideal conductive heat transfer. The conductive equation is
\[ \rho c \left( \frac{\partial T}{\partial t} \right) = \kappa \left( \frac{\partial T}{\partial z} \right), \]

where \( \rho \), c, and \( \kappa \) are density, heat capacity, and heat conductivity of the layer of the soil or snow between the two sensors. By assuming the vertical uniformity of those values in the layer at any specific time, the above equation can be written as

\[ \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2}, \]

where \( \lambda \equiv \kappa/\rho c \) is the thermal diffusivity. Suppose the diurnal thermal forcing is the most powerful and influential cycle to the thermal change in the shallow soil layers of interest. At the upper boundary, i.e. ground surface, (with \( A \) the amplitude, \( \omega \) for the frequency of the 24-hour cycle, and \( \phi \) the phase shift)

\[ T_a (t) = A \sin(\omega t + \phi), \]

the temperature at the bottom of the layer is given by

\[ T_b (t) = A \exp(-\chi/d) \sin(\omega t - \chi/d + \phi), \]

where \( d \) is the depth of the layer, and \( \chi \) is given by \( \sqrt{2\lambda/\omega} \). Therefore, the thermal diffusivity of the layer \( \lambda \) can be estimated either by the damping ratio of the amplitude or phase shift in the temperature cycle between the layers.

Figure 2 shows an example of the analysis. Although this is a snow temperature time series, the general principle of this methodology can be translated to the cases for soil. The left panel shows the original time series of snow temperature at the height of 100, 40, and 5 cm from the ground for the three winters from 2005 to 2008 at the UT site. By visual inspection it is a rational assumption that the highest sensor kept recording the air temperature for the whole period. The right panels show the estimation of the thermal diffusivity of the layers between 5 and 40 cm obtained by the ratio of the amplitude of the diurnal cycle.

Here, some technical remarks on the methodology and the caveats on the interpretation of the results, as well as notes for future extension of the analysis are given below. Firstly, although theoretically both amplitude damping ratio and phase shift can be used for the estimation, the results from the amplitude damping is more robust in most of the case. Secondly, the more favored and capable wavelet technique for this application proved to be the Morlet function, rather than the derivatives of Gaussian.

Thirdly, the current method cannot exclude the effects of change in soil moisture, which is one of the most influential factors governing the soil thermal property. Independent measurement of soil moisture is very critical to interpret the results. In addition, decomposition of the inferred value of thermal diffusivity \( \lambda \) to thermal conductivity \( \kappa \) and heat capacity \( c \) is not trivial. Independent measurement of heat capacity puts values on the ad hoc observation of these three variables at the sites. This methodology will not work when the phase change of water takes place.
Fig. 2. Example of the results of analysis on the thermal property (thermal diffusivity) from the observed temperature time series. a) Original time series of the observed temperature at UT (Upland arctic tundra) for the winters from 2005 to 2008 at the height of (from above) 100, 40, and 5 cm from the ground surface (scales are shown at side of each line). b) Thermal diffusivity between the snow layer 5-40 cm computed from the ratio of the wavelet amplitude corresponding to the 24 hour cycle.

Role of Snow in Land-Atmosphere Interactions (Jessie Cherry, Kazuyuki Saito)

New instrumentation on Seward Peninsula was with 2 cm resolution thermocouple strings in the snowpack at Kougarok sites (Figure 3a) to evaluate the soil-snow-atmosphere interactions, and to compare the results between Arctic (Alaska) and mid-latitude (New York) regions.

Fig. 3. a) Instrumentation at the Kougarok site. b) Analysis of historical data of soil, snow and air temperatures. Plot made by Marla Schwartz (undergraduate summer intern).

Presentations
Annual meeting of Japan Snow and Ice Society, Sapporo, 09/29-10/3, 2008. Saito, K. Hydro-thermal sensitivity of Arctic soil to thermal representation evaluated by an
AGCM. — Climatology and Inter-annual variability — (Poster).

References
Theme 7 State of snow and ice and variability
7-2: Non-uniform distribution of snow cover

Introduction
Snow is one of the important processes for energy balance in the earth climate system. The lack of sub-grid snow-distribution representations in most climate models has been identified as a deficiency in snow-cover evolution and atmospheric interaction simulations (Loth and Graf, 1998; Pomeroy et al., 1998; Slater et al., 2001; Takata et al., 2003; Liston, 2004). The widely observable satellite remote sensing technique also recognizes that sub-grid snow-distribution causes uncertainty. For better understanding of snow processes in the arctic climate system and for reducing the uncertainty of reliably estimating the amount of snow in the cryosphere, it is necessary to improve representations of non-uniform snow cover within regional and global weather, climate, and hydrologic models.

Objectives
This study is aimed at estimating the significant energy effect of non-uniform snow to the air, ground, and vegetation in Alaska and its interannual variation. It uses a newly developed model based on in situ observations and clarifies the differences in snow-cover characteristics in Siberia and Alaska. The study contributes to a better understanding of snow processes in the arctic climate system and reduces the uncertainty of reliably estimating the amount of snow in the cryosphere.

Participants
PI: Sugiura
Co-Is: Aoki, Enomoto, Kim, Koike, Komori, Saito, Yamazaki, Post-Doctoral Fellow
Study summation
Sugiura (JAMSTEC)

In-site Observation
Busey (IARC), Kim (IARC), Saito (IARC), Post-Doctoral Fellow (Nakai, IARC)

Modeling
- Regional/Basin scale, Yamazaki (Tohoku Univ.)
- Global scale, Enomoto (JAMSTEC), Komori (JAMSTEC)

Remote Sensing
- Visible/Near infrared, Aoki (MRI)
- Microwave, Koike (Univ. Tokyo)

Methodology
1. AWSs for heat balance analyses at monitoring and validation sites (such as forest, grass, moss and also the coast near sea ice and the mountains) for heterogeneity observations of snow-cover characteristics.
2. Physically based new snow-atmosphere-ground-vegetation model combined with land surface (Yamazaki, 2001) and blowing snow models (Sugiura, 2006) in order to improve the understanding of the heterogeneity of snow-cover characteristics.
3. In situ Alaskan historical snow data and snow condition products by the GCM and the satellite for quantitative intercomparison.
Activities for 2009FY
Planned activities in the first year 2009FY for Theme 7-2 of JAMTEC-IARC Collaboration Study were as follows:
1. Selection and setup of monitoring and validation sites of heterogeneity of snow-cover characteristics at typical places such as forest, grass, moss, and also the coast near sea ice and the mountains. (According to the circumstances, the setup of the sites may be carried out after the next fiscal year.)
3. Collection of in situ Alaskan historical snow data and snow condition products by the GCM and the satellite for quantitative intercomparison.

Results of 2009FY
Conducted official trips
- Snow survey in north Alaska, March 7–13, 2009
- Site inspection near Fairbanks and in south Alaska, October 22–28, 2009
- Data collection at UAF Smith Lake site, December 16–17, 2009
- Planned snow survey near Fairbanks and in south Alaska in 2009FY, March 14–19, 2010

Conducted activities
- UAF Smith Lake site
  Instruments installed at UAF Smith Lake site in 2008FY were maintained. The instruments such as snow pillow, distance sensor, air temperature and related humidity sensor, interval digital camera, and precipitation gauge have been installed at the UAF Smith Lake site (Fig. 1).

Fig. 1. Overview of instruments at the Smith Lake site.

The distance sensor for the snow pillow to investigate time-series variation of the snow water equivalent, including the snow depth and snow density was installed at the middle of winter, January 22, 2009 (Fig. 2). The distance sensor measures the
snow depth above the snow pillow. The snow depth increased in response to several snowfall events and disappeared on April 18, 2009. The interval digital camera with an interval of three hours also had evidence of the snow disappearance date in Fig. 3.

**Fig. 2.** Time series of the snow depth above the snow pillow.

**Fig. 3.** Snow disappearance date by an interval digital camera. a) 12:00 PM, April 27. b) 12:00 PM, April 28. c) 12:00 PM, April 29, 2009.

- **Snow survey in north Alaska**

  The traverse line in northern Alaska is set to the north of Fairbanks, extending over the Yukon River basin characterized by taiga and the North Slope characterized by tundra. The snow density of the North Slope is higher than that of the Yukon River basin in the same stage.

**Fig. 4.** Altitude dependence on snow water equivalent in north Alaska by snow survey on March, 2009. x: point data alongside the Dalton Highway in the North Slope. •: point data alongside the Dalton Highway in the Yukon River basin.
- **Supersite**
In order to contribute to the JAMSTEC-IARC Collaboration Study for improved understanding of the nature and predictability of climate variability and regional aspects of global environmental change in the Arctic, a supersite plan entitled “Supersite plan in Alaska under Joint Research Activities between the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the International Arctic Research Center (IARC)” was developed.

The Caribou-Poker Creeks Research Watershed (CPCRW) and the Poker Flat Research Range (PFRR) surrounding area was selected in the supersite. The tower will be built in the Poker Flat Research Range (PFRR).

- **Physically based snow-atmosphere-ground-vegetation model**
The performance of land surface (Yamazaki, 2001) and blowing snow (Sugiura, 2006) models, as shown in Fig. 5, was confirmed. The land surface model describes snow, vegetation, and soil processes, and the blowing snow model describes a blowing snow process one-dimensionally.

![Fig. 5. Parts of a physically based snow-atmosphere-ground-vegetation process model. a) 2LM: Yamazaki, 2001. b) FUBUKI model: Sugiura, 2006.](image)

- **Data collection**
Several in situ Alaskan historical snow data such as snow water equivalent and precipitation, and snow condition products by the GCM and the satellite for quantitative intercomparison were obtained. Figure 6 shows one example of the obtained global satellite data of the monthly snow water equivalent by AMSR-E from June 2002 to December 2009.

![Fig. 6. Monthly snow water equivalent by AMSR-E on December 2009.](image)
Supportive-framework

As a supportive-framework for theme 7-2, the following research was concluded in 2009FY.

1. JAXA GCOM C1 RA (2009FY-2012FY)
   PI: Aoki (Sugiura as Co–Investigator)
2. Joint research between JAMSTEC and UT (2009FY-2011FY)
   PI: Sugiura (Supervisor: Ohata) and Tsutsui (Supervisor: Koike)

These continuous accumulated efforts will enable us to carry out further analysis and to accelerate progress towards the achievement of objectives in Theme 7-2.

Presentations

**Theme 8-1 Evaluation of the greenhouse gas budget of terrestrial ecosystems in the arctic region**

**Introduction**

Human-induced global warming is predicted to exert severe impacts on biogeochemical and ecological systems, especially in the arctic region. Terrestrial ecosystems have feedback processes to the climatic change through not only changes in physical properties (e.g., albedo, roughness, and surface conductance) but also changes in the long-lived greenhouse gases budget (GHGs: CO₂, CH₄, and N₂O). In particular, melting of a vast area of permafrost will result in a huge amount of carbon and GHG emissions. However, it is still difficult to estimate how much GHGs would be released as a result of climatic change, due to the lack of reliable monitoring data and immaturity of process-based ecosystem models. This insufficient understanding of the arctic processes may lead to significant uncertainty in the climate prediction using coupled climate models or earth-system models. The arctic ecosystems are undergoing not only climate change but also various human impacts and disturbances. For example, vast areas of boreal forests are burnt every year, and exploitation of natural resources should affect wildlife such as animals, insects, fish, and microbes. To estimate these complicated impacts, we need some integrated models of the arctic systems.

**Objectives**

The primary objective of Theme 8-1 is to develop a terrestrial ecosystem model simulating the atmosphere-ecosystem exchange of trace gases, especially of GHGs, including specific processes in the arctic regions such as wildfire and permafrost. The model will also simulate carbon and nitrogen cycles within ecosystems, by which dynamics of biomass and leaf area index (LAI) would be appropriately retrieved. The model should be validated using observational data (1) at site-scale for GHG exchange and (2) at regional-scale for biomass and LAI distribution. Using the calibrated model, site to regional scale simulations will be conducted to evaluate GHG budget, firstly for the present era and secondly for the future on the basis of climate projection scenarios.

**Participants**

**PI:** Akihiko Ito (JAMSTEC-RIGC / NIES-CGER)

**Co-Is:** Motoko Inatomi, Rikie Suzuki (JAMSTEC-RIGC), Yongwon Kim, Taro Nakai (IARC)

**Methodology**

A process-based model simulating atmosphere-ecosystem exchange of GHGs is under development on the basis of a simple carbon cycle model (Sim-CYCLE: Ito and Oikawa 2002) and a trace gas model (VISIT: Ito in press). By adding processes specific to the arctic region, an integrated model of an arctic GHG and trace gas exchange model will be developed. Model validation will be conducted through comparison with observational data such as chamber-measured GHG flux and a satellite-derived aboveground biomass map.

**Model description**

VISIT (Vegetation Integrative SImulator for Trace gases) is a process-based terrestrial ecosystem model, focusing on carbon cycle, nitrogen cycle, and trace gas exchange with the atmosphere. In this model, ecosystem carbon storage occurs in four
sectors — trees, floor plants, litter, and humus — each of which is divided into coupled sub-compartments (Fig. 1). For example, the tree sector is composed of leaf, stem, and root compartments, and the humus sector comprises labile, intermediate, and passive compartments. The stem litter compartment represents coarse woody debris. Net ecosystem CO$_2$ exchange (NEE, g C m$^{-2}$ day$^{-1}$) is calculated by

\[ \text{NEE} = \text{GPP} + \text{RE}, \]

where GPP and RE are gross primary production and ecosystem respiration, respectively (a negative NEE value represents uptake of carbon from the atmosphere by the ecosystem). GPP is estimated at 30-min time steps by using the sun-shade canopy model of de Pury and Farquhar (1997), which separately evaluates absorption of diffuse and beam radiation and incorporates biochemical CO$_2$ assimilation processes. On the basis of single-leaf gas-exchange measurements, Ito et al. (2006) parameterized seasonal changes in leaf mass per leaf area (LMA), photosynthetic capacity, and dark respiration of deciduous tree species at Takayama. In this model, the leaf phenology of the deciduous tree canopy is determined by the cumulative temperature above or below a threshold temperature, and LAI is calculated from the LMA and leaf biomass. RE comprises autotrophic respiration by plants and heterotrophic respiration by microbes. Autotrophic respiration consists of maintenance and construction components for each tree and floor plant compartment. Heterotrophic respiration in the litter and humus compartments is a function of soil temperature and moisture content. Ito et al. (2007) examined the performance of this respiration scheme by using flux observation data for soil (including root and microbial efflux) and ecosystem respiration at Takayama. NEE simulated by the model was validated against the eddy-covariance measurements, and the model has been successfully used to evaluate the regional carbon budget evaluation of East Asia (Ito 2008). The VISIT model simulates intra-ecosystem carbon flows associated with, for example, litter fall, allocation, growth, and leaf phenology at daily time steps, using climate data on air temperature, soil temperature, air humidity, solar radiation, cloudiness, precipitation, and wind velocity.

![Fig.1. Schematic diagram of biogeochemical cycles in VISIT.](image)
**Activities for 2009FY**  
*Field survey in search of the core site*

The first field activity to select the core site around Fairbanks, for intensive assessment of this project, was conducted July 27–30, 2009. We visited Bonanza Creek and Poker Flat (Fig. 2), each of which is on discontinuous permafrost and covered with typical black spruce forest. Also, we visited a field measurement site in the vicinity of the University of Alaska campus. Intensive discussion was made on the selection and establishment of the core site.

![Map of Alaska area, indicating positions of IARC, Bonanza Creek, and Poker Flat.](image)

**Preliminary model simulation**

We conducted a preliminary simulation to examine whether the present version of VISIT is applicable to the Arctic region and to find out which component and process should be modified. The preliminary simulation was performed using a generic parameter set of evergreen needle-leaved forest of VISIT. The long-term climate condition was derived from the NCEP/NCAR reanalysis data for the Fairbanks area (63°N, 147°W) and used as model input data without correction (Fig. 3).
Fig. 3. Long-term climate condition (annual precipitation and mean temperature) for the Fairbanks area derived from the NCEP/NCAR reanalysis data.

Results of 2009FY

Preliminary simulation

Carbon budget and GHG exchange were simulated using generic data (i.e., no field data were used) for a black spruce forest around Fairbanks, Alaska.

Fig. 4. Simulated carbon accumulation into a black spruce forest around Fairbanks during the first 500 years of simulation.
Fig. 5. Simulated greenhouse gas fluxes at a black spruce forest around Fairbanks: upper, soil respiration CO$_2$ flux; middle, microbial CH$_4$ oxidation uptake flux; lower, N$_2$O emission flux. For CH$_4$ and N$_2$O fluxes, results by difference estimation schemes are shown.

GHG fluxes were simulated by VISIT using a couple of estimation schemes. It was found that different seasonal changes in GHG exchange were simulated by these
schemes. For example, burst N2O emission in spring was simulated only by the Parton’s scheme, in which increased denitrification as a result of inundation due to snow melting was captured. In our forthcoming study, we will compare the simulated GHG fluxes and carbon budget with the literature (e.g., Kim and Tanaka 2003) and observational data obtained by the joint JAMSTEC-IARC activity. Also, several sensitivity simulations will be conducted in terms of wildfire and climatic change.

References
Theme 8-2 Monitoring of flux-measurements of CO₂ and CH₄ in tundra and boreal forest soils, Alaska

Introduction

Boreal black spruce forests typically have relatively open canopies that allow a significant portion of incoming radiation to reach the ground vegetation (Baldocchi et al., 2000). Forest floor GPP (Gross Primary Productivity) is thus a potentially important process that can represent a significant portion of C assimilation in such ecosystems (Gaumout-Guay et al., 2009) and can be as high as 50% on certain days (Goulden and Crill, 1997). The GPP of the forest floor vegetation depends on favorable light intensity, temperature, and moisture conditions (Raich and Schlesinger, 1992; Lavigne et al., 1997; Rayment and Javis, 2000; Xu and Qi, 2001; Swanson and Flanagan, 2001; Kolari et al., 2006; Bergeron et al., 2009) and on the composition and relative presence of different forest floor communities in the ecosystems (O’Connell et al., 2003; Heijmans et al., 2004).

The Re (Ecosystem Respiration) includes respiration by aboveground vegetation (stems, branches, twigs, and leaves) and soil. Soil respiration is a dominant component of CO₂ exchange in the boreal ecosystem, accounting for at least half of Re. The temporal variability of respiratory metabolism is influenced mostly by temperature and moisture environments (Davidson et al., 1998; Swanson and Flanagan, 2001; Gaumont-Guay et al., 2006a). Aboveground and belowground C exchange processes contributing to Re can respond in different ways to the seasonal variation of temperatures in air and soil, to the availability of water, and to substrate content/type (Davidson et al., 2006; Jassal et al., 2007; Bergeron et al., 2009).

The CO₂ exchange between the boreal black spruce forest and the atmosphere is complex, with significant contributions by five physiological processes: black spruce photosynthesis, black spruce respiration, moss photosynthesis, moss respiration, and heterotrophic respiration (Bonan and Shugart, 1989; Goulden and Crill, 1997). Although the five processes are important portions of forest C exchange, the roles of tussock and lichen on a boreal black spruce forest floor cannot be overlooked. The distribution area in the Northern Hemisphere of tussock, moss, and lichen is $6.5 \times 10^{12}$ m² (Whalen and Reeburgh, 1998), and tussock is an important CO₂ and CH₄ source in black spruce forest soils during the winter (Kim et al., 2007). Hence, information on the rates of and controls on each of these processes is needed to improve understanding of the current and future carbon balance of the boreal forest.

Objectives

Research objectives are to:
1. Estimate CO₂ flux-measurement on the ground level of boreal forest during the growing season.
2. Understand carbon dynamics and evaluate regional carbon budget.

Participants
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UAF: Taro Nakai (IARC), Katey Walter (WERC)
Methodology

Before the construction of the super site in Poker Flat Research Range (PFRR), the monitoring of CO₂ and CH₄ flux-measurements was carried out at the UAF site. The automated open/close chamber (AOCC) system was installed on the typical ground plants such as tussock, lichen, feather moss, and sphagnum moss, and has used two kinds of chambers, transparent and non-transparent, for estimation of GPP and Re. The system consists of eight soil chambers (30 cm high, 40 cm diameter), eight chamber bases (15 cm high, 60 cm diameter), a compressor for the chamber lid to open and close, a mini-pump (5 L/min, Japan), desiccant tube (3 cm ID, 20 cm long) filled with Drierite (Fisher Scientific, USA), CO₂ gas analyzer (Licor-820, Licor, Nebraska, USA), and two dataloggers (CR-10X, Campbell Scientific Inc., Lincoln, USA) for CO₂ data and environmental data. The frame of the chamber was made of aluminum, and a transparent high-density polyethylene (HDPE) film was fixed to the frame with sealant. Two fans in each chamber are active for the homogeneous air sample when the lid is closed; the air is transported to the CO₂ gas analyzer and moved in a cycle by the pump.

The chamber was placed on the four representative floor vegetations on black spruce forest soil. Six are transparent chambers for the GPP estimates, and two on sphagnum and tussock are non-transparent for the estimation of Re. The observation period was from July 22 to September 24, 2007, and from May 20 to October 18, 2008, during the growing season. Each chamber measured the change in CO₂ concentration for 3.75 minutes.

Soil temperatures in tussock and sphagnum, and soil moisture in sphagnum were monitored. Soil temperatures were measured with thermocouples at 0, 5, 10, 15, and 30 cm below the tussock surface, and at 0, 2, 5, 10, and 15 cm below the sphagnum surface. Soil moisture with the TDR (Time Domain Reflectometry) was measured at a depth of 10 cm below the sphagnum surface. The measuring interval was 30 seconds. The measured data were stored in the datalogger.

Activities for 2009FY

The system has operated on the ground in a black spruce forest, Interior Alaska, from May to October for the growing season of 2009. Nakai and I have visited several times in the PFRR for the selection of a super site.

Results of 2009FY

Diurnal variation of floor CO₂ exchange

Diurnal variation of GPP in lichen and feather moss was not related to the changes in environmental factors. Average GPP is 0.049±0.019 mgCO₂/m²/s (range: -0.009 to 0.095 mgCO₂/m²/s) in lichen, and 0.088±0.065 mgCO₂/m²/s (range: -0.045 to 0.29 mgCO₂/m²/s) in feather moss, respectively. In the sphagnum moss, average GPP, Re, and NEE are 0.017±0.032 (range: -0.067 to 0.092 mgCO₂/m²/s), 0.048±0.018 mgCO₂/m²/s (range: 0.003 to 0.099 mgCO₂/m²/s), and 0.023±0.035 mgCO₂/m²/s (range: -0.053 to 0.13 mgCO₂/m²/s), respectively. In the tussock regime, average GPP, Re, and NEE are 0.088±0.065 (range: -0.045 to 0.29 mgCO₂/m²/s), 0.042±0.042 mgCO₂/m²/s (range: -0.16 to 0.22 mgCO₂/m²/s), and -0.046±0.069 mgCO₂/m²/s (range: -0.42 to 0.11 mgCO₂/m²/s), respectively. Sphagnum moss was a CO₂ release to the atmosphere; on the other hand, tussock was an atmospheric CO₂ sink during the observed period of 2008.

Temperature is a significant regulator in determining the forest floor CO₂ exchange (e.g., GPP and Re) in a boreal forest (Davidson et al., 1998; Rayment and...
Javis, 2000; Xu and Qi, 2001; Gaumont-Guay et al., 2006a, b, 2008). Although there are many reports on temperature sensitivity of the CO2 exchange, the CO2 exchange measured in this study was much lower in relation to temperature during the growing season of 2008. This is due to extremely heavy rainfall at the end of July of 2008, enough to flood a local river. In order to understand the temperature sensitivity on the floor CO2 exchange, we fit the relationship between the exchange and temperatures in air and soil with an exponential curve as the equation

\[ SR = \beta_0 e^{\beta_1 \cdot T} \]  

where \( SR \) is measured floor CO2 exchange, \( T \) is temperatures in air and soil, and \( \beta_0 \) and \( \beta_1 \) are constants. This exponential relationship is commonly used to represent CO2 exchange as a function of temperature (Lavigne et al., 1997; Davidson et al., 1998; Rayment and Javis, 2000; Xu and Qi, 2001; Gaumont-Guay et al., 2006a, b, 2008).

The Q10 values were calculated as in Davidson et al. (1998)

\[ Q_{10} = e^{\beta_1 \cdot 10} \]  

Here, we calculated Q10 values for the GPP of only sphagnum moss on temperatures in air, 2, 5, and 10 cm below the sphagnum surface for June (DOY 153–153), July (DOY 184–185), August (DOY 215–216), and September (DOY 244–245) of 2008. The Q10 values increase with the depth, indicating that the Q10 value is much more sensitive to the lower temperature at deeper depth. The correlation coefficient (R^2) decreases with depth, showing that temperatures in air and 2 cm below the sphagnum surface are suitable for estimation of the Q10 during 2008. In addition, during the rainy period (DOY 215–216), the Q10 value and the coefficient are much lower than those in the dry period. We discuss the Q10 values on average daily GPP and Re of the floor vegetations during 2007 and 2008 in next section.

**Seasonal variation of environmental factors and floor CO2 exchange**

The seasonal variations in daily averages for temperatures in tussock and sphagnum moss, soil moisture in sphagnum moss, and precipitation, air temperature, and PAR during the observing periods of 2007 and 2008 are shown in Figure 1. In Figure 1, temperatures on the surface of tussock (1a and 1e) and sphagnum (1b and 1f) were not shown due to the similarity of air temperature. Also, the temperature was not measured at 2 cm depth below the sphagnum surface during 2007.
Fig. 1. The seasonal variations in daily averages for temperatures in tussock and sphagnum moss, soil moisture in sphagnum moss, and precipitation, air temperature, and PAR during the observing periods of 2007 and 2008.

Fig. 2. The seasonal variations in daily GPP on lichen and feather moss, and GPP, Re, and NEE on tussock and sphagnum moss during the observing periods of 2007 and 2008.
Figure 2 shows seasonal variations in daily GPP on lichen and feather moss, and GPP, Re, and NEE on tussock and sphagnum moss during the observing periods of 2007 and 2008. Average GPP of lichen and feather (Figure 2a and 2e) moss is 0.094±0.024 and 0.117±0.038 mgCO$_2$/m$^2$/s in 2007, and 0.050±0.012 and 0.027±0.010 mgCO$_2$/m$^2$/s in 2008. This indicates that the GPP of 2007 is 1.9- and 4.3-fold higher than that of 2008 despite a short observing period in 2007.

Recently, Bergeron et al. (2009) reported that GPP ranged from 0.022 to 0.31 (average 0.17) mgCO$_2$/m$^2$/s in lichen, and 0.042 to 0.44 (average: 0.26) mgCO$_2$/m$^2$/s in feather moss in a black spruce forest in Canada (49.692°N, 74.342W) during three growing seasons, which is much higher than ours. Average GPP and Re of tussock (Figure 2b and 2f) are 0.133±0.066 and 0.260±0.091 mgCO$_2$/m$^2$/s in 2007, and 0.082±0.029 and 0.043±0.013 mgCO$_2$/m$^2$/s in 2008. This shows that GPP and Re of 2007 is 1.6- and 6-fold higher than those of 2008. Average GPP and Re of sphagnum moss (Figure 2c and 2g) are 0.058±0.011 and 0.064±0.018 mgCO$_2$/m$^2$/s in 2007, and 0.022±0.021 and 0.050±0.014 mgCO$_2$/m$^2$/s in 2008. This indicates that GPP and Re of 2007 is 2.7- and 1.3-fold larger than those of 2008 as shown in the other three floor vegetation, respectively. In a black spruce stand of eastern Canada, GPP of sphagnum ranged from 0.042 to 0.31 (average 0.22) mgCO$_2$/m$^2$/s during three growing seasons, which is much higher than ours (Bergeron et al., 2009). Rayment and Jarvis (1997) reported the Re in a feather moss dominated area that ranges from 0.11 to 0.29 mgCO$_2$/m$^2$/s, in conjunction with changes in soil temperature (at 5 cm depth) from 7 to 18°C in the BOREAS project site during August and September. In the same site, the Re was 0.12±0.06 mgCO$_2$/m$^2$/s in the feather moss community and 0.11±0.03 mgCO$_2$/m$^2$/s in the sphagnum (Swanson and Flanagan, 2001). Their data are much higher than our results in this study despite the presence of the same black spruce forest. Although the floor vegetation are the same, the higher GPP and Re differences between our site and theirs resulted in different annual air temperature (-2.9 and 0.0 °C) and precipitation (260 and 960 mm). This suggests that the spatial variability of Re in forest floor vegetation has been related to the physical (temperature, moisture, micro-topography, porosity, organic horizon depth), chemical (nutrient status of mineral and organic horizons, organic matter quantity and quality), and biological (microbial biomass and community composition) properties of the soil, which can influence either the production of CO$_2$, its transport to the surface, or both (Rayment and Jarvis, 2000; Xu and Qi, 2001; Heijmans et al., 2004; Khomik et al., 2006; Kolari et al., 2006; Bergeron et al., 2009).

The average NEE of tussock and sphagnum moss (Figure 2d and 2h) denotes 0.127±0.049 and 0.006±0.018 mgCO$_2$/m$^2$/s in 2007, and -0.039±0.025 and 0.028±0.017 mgCO$_2$/m$^2$/s in 2008. Positive NEE indicates a CO$_2$ release to the atmosphere, and negative means an atmospheric CO$_2$ uptake. During the observing periods of 2007 and 2008, the accumulative floor CO$_2$ exchange rates are estimated. The accumulative GPP of lichen and feather moss are 139 and 174 gC/m$^2$ in 2007 and 122 and 67 gC/m$^2$ in 2008, respectively. The accumulative GPP, Re, and NEE of tussock are 197, 386, and 189 gC/m$^2$ in 2007 and 202, 106, and -96 gC/m$^2$ in 2008, respectively. The accumulative GPP, Re, and NEE of sphagnum moss are 86, 94, and 8 gC/m$^2$ in 2007 and 53, 122, and 69 gC/m$^2$ in 2008, respectively. This indicates that NEE of tussock and sphagnum moss in 2007 is 4.5-fold higher than in 2008 and 0.2-fold lower than in 2008, respectively. Remarkably, tussock was an abundant CO$_2$ source during 2007; however, the same tussock became an atmospheric CO$_2$ sink during 2008. On the other hand, sphagnum moss was a much stronger CO$_2$ source during 2008 than during 2007.
As previously described, temperature is a significant environmental factor in determining the floor CO$_2$ exchange on the terrestrial ecosystem (Raich and Schlesinger, 1992; Lavigne et al., 1997; Davidson et al., 1998; Rayment and Javis, 2000; Xu and Qi, 2001; Gaumont-Guay et al., 2006a, b, 2008). Q$_{10}$ values estimated on a growing season basis not only represent the temperature-dependent processes (Davidson et al., 2006; Bergeron et al., 2009) but also include the phenological effect (e.g., root growth stage) and microbial community and population shifts (Yuste et al., 2004). Hence, our findings demonstrate that the dynamics of the processes influencing the temperature dependence of GPP, Re, and NEE are to some degree affected by forest floor vegetation type, which is, to some extent, a reflection of the underlying soil properties (Bergeron et al., 2009).

On the basis of air temperature, Q$_{10}$ values in 2007 are higher than those in 2008 for four vegetations. Air temperature explains 77–95% of the variability in GPP and Re for lichen, feather moss, tussock, and sphagnum moss on a black spruce forest floor, Interior Alaska. This demonstrates that air temperature is a significant regulator in influencing GPP and Re on the floor vegetation in a black spruce stand during the growing season of 2007. On the temperatures of floor vegetation in 2007, Q$_{10}$ values show increasing trends with depth; however, the values do not indicate any pattern in 2008. This suggests that the simulated annual GPP, Re, and NEE for these floor vegetation can be estimated with Q$_{10}$ value based on air temperature during 2007. Q$_{10}$ values in deeper depth ranged from 5.18 to 24.9 at 30 cm depth beneath tussock, and from 5.13 to 22.8 at 15 cm beneath sphagnum. Except for 15 cm below the tussock surface and 30 cm below the sphagnum surface in 2007, soil temperatures in tussock and sphagnum moss elucidate 77–93% and 66–88% % of variability in GPP, Re, and NEE for these floor vegetation near the soil layer. Most floor CO$_2$ exchange rates occur in the upper soil layers in the forest ecosystem (Drewitt et al., 2005; Jassal et al., 2005). These results describe the need to account for different ground-cover vegetation types in soil and ecosystem C exchange studies as they may reflect the tempo-spatial variability of soil properties and the distribution of respiratory-photosynthetic processes on soil surface and in the soil profile.

Q$_{10}$ values in a black spruce forest floor ranged from 3.22–4.36 for feather moss, 3.52–4.42 for lichen, and 3.33–4.42 for sphagnum moss. The shallow soil temperature explained 67–86% of the temporal variation of soil respiration under the ground cover types (Bergeron et al., 2009).

In order to estimate annual GPP, Re, and NEE on these floor vegetation, we applied Q$_{10}$ values calculated by the relationship between the floor CO$_2$ exchange and the air temperature in 2007. In 2008, as previously described, the relationship between the exchange and air temperature was much lower because soil moisture showed an unusual rise related to a heavy rainfall event. Simulated GPP, Re, and NEE during the growing season are overwhelmingly higher than during the non-growing season. During the non-growing season, the annual GPP estimated in these floor vegetation appears remarkable under lower air temperature conditions. The Re of tussock is much higher than the GPP and the GPP of sphagnum moss was also higher than the Re during the growing season. This demonstrates that tussock and sphagnum moss were important roles in emitting CO$_2$ to the atmosphere in a black spruce forest during 2007.

The contributions (%) of GPP and Re on the ground vegetation to the simulated annual GPP and Re and to the black spruce forest (Ueyama and Harazono, 2008) for DOY 1–120, 121–243, and 244–365. The contributions of seasonal GPP indicate 56–71% of annual GPP in floor vegetation during the growing season; however, the
contribution is 8–18% to the GPP in the black spruce forest, suggesting that the GPP of black spruce is dominant over the ground vegetations during the growing season. On the other hand, during the non-growing season, the contributions of GPP are 11–19% (DOY 1–120) and 18–26% (DOY 244–365) of annual GPP in the ground plants; however, contributions to the black spruce forest denote 63–72% (DOY 1–120) and 20–25% (DOY 244–365). This demonstrates that the floor CO₂ emission is a component of the regional carbon budget, along with the contribution of winter soil respiration (Kim et al., 2007). In addition, the simulated NEE in tussock and sphagnum is 687 and -14 gC/m², respectively, suggesting that tussock is abundant atmospheric CO₂ source. On the other hand, in the mature black spruce forest of the BOREAS project during the growing season, the NEE in feather moss was 255 gC/m², indicating a release of carbon to the atmosphere. This net loss of carbon in sphagnum moss was the difference between the GPP of 141 gC/m² and the Re of 396 gC/m². Moss GPP contributed approximately 13% of the total ecosystem GPP (Swanson and Flanagan, 2001), corresponds to our results of 11%. Bergeron et al. (2009) reported that the contribution of GPP in floor vegetations to the total ecosystem GPP was not constant over the course of the snow-free season, varying from 13 to 24%. Their NEE in the moss corresponds to 20–37% of the NEE in tussock in our study, demonstrating that the tussock has an important role in emitting CO₂ to the atmosphere in a black spruce forest, Interior Alaska. Therefore, both moss and tussock play significant roles in forest floor CO₂ exchange and contribute to the black spruce forest carbon cycle/budget. Furthermore, we additionally need to (1) monitor GPP and Re in different height tussocks and in inter-tussock for the contribution to the forest ecosystem, and (2) measure the heterotrophic respiration in representative on-ground vegetations of a black spruce forest, for the estimation of the NEP (Net Ecosystem Productivity).

Presentations
Yongwon Kim, Mamoru Ishii, and Yuji Kodama, Regulating factors on continuous winter CO₂ flux in the black spruce forest soils, interior Alaska, 16th International Symposium on Polar Sciences: Polar Exploration with ARAON, Incheon, Korea, June 10-12, 2009.
Yongwon Kim, Seong-deog Kim, Woongji Kim, and Tomoyuki Wada, Monitoring of Soil Respiration in Black Spruce Forest Soils, Interior Alaska, 8th International Carbon Dioxide Conference, Jena, Germany, September 13-19, 2009.
9-1: Evolution and validation of a land surface model

Introduction

The structure and functioning of arctic terrestrial ecosystems are greatly sensitive to changes in climate. Evidence continues to mount that warming experienced in the arctic region during the past few decades has been affecting the structure and functioning of the arctic terrestrial ecosystems (Serreze et al., 2000). All components of the Arctic are interrelated through a network of linkages, feedbacks, and multi-dependent interactions. A change in one variable in a part of the system can initiate a cascade of regional effects and have global ramifications. It is therefore important to understand the consequences that changes will have on the functioning of the arctic system.

Responses of the arctic terrestrial ecosystems to global warming are in turn feedback to the global climate, influencing the exchange of water, energy, and gases with the atmosphere in several ways. Observations reported an increase in the number of shrubs in tundra (Chapin et al., 1995) and an increased and early greening of the arctic ecosystems (Buermann et al., 2003). Expansion of shrub cover has its own positive feedback on climate because of the lower albedo of shrubs compared to tundra and because areas with shrubs have a lower snow albedo, and consequently earlier snowmelt than snow-covered tundra (Chapin et al., 2005). Changes in evapotranspiration (ET) associated with the extended growing season and increased greening affect the regional precipitation system, which has consequences for river runoff and ET that depend additionally on precipitation inputs to terrestrial ecosystems.

In the Arctic during winter, soils are regularly frozen. The freeze-thaw cycle modulates the change of both soil temperature and the overlying air temperature due to release or absorption of latent heat during freezing and thawing processes. These processes influence the thermal and hydrological properties of the soil. Thermal conductivity of ice is about four times higher than that of water and volumetric heat capacity of ice is half that of water. Changes in these properties definitely affect the surface water and energy balances, which in turn feedback to the atmospheric climate. Ice also impedes water flow within the soil, which is rather inefficient to capillary action, infiltration, and percolation. The presence of ice significantly decreases hydraulic conductivity of a porous medium. Thus, much water accumulates near the freezing front. In winter, the low air temperature, and, hence, the low saturation of water vapor as well as the frequently stable stratification of the lower atmospheric boundary layer lead to less evaporation. Moreover, transpiration during winter is very low compared to transpiration during moderate weather conditions. Thus, moisture will be stored in frozen soils and may enhance spring peak flood events.

In the Arctic, where cold temperatures inhibit decomposition of dead vegetation, soil organic material can build up over time forming peat deposits. Organic material acts as an insulator, with its low thermal conductivity and relatively high heat capacity modulating the transfer of energy down into the soil and out of the soil, typically leading to cooler soil temperatures (Bonan and Shugart, 1989). Partly as a consequence of this, permafrost is present at warmer annual mean air temperatures. An addition characteristic of organic or peat soil is its high porosity and its correspondingly high hydraulic conductivity. Theses characteristics generate soil conditions in peatlands that are typified by saturated sub-surface soil with shallow depths to the water table (Hinzman et al., 1991). The higher soil temperature caused by global warming subsequently increases the decomposition of organic matter within
the soil. The climate-change-induced decrease of organic matter alters the thermal and hydraulic properties of organic soil, impacting the surface energy fluxes, which in turn feeds back to the atmosphere.

A snow layer on the soil surface delays water input into the land surface and insulates the soil allowing only little heat exchange between the soil and atmosphere. The processes of snow accumulation and snowmelt further affect the energy budget due to the change in albedo and in emissivity. The strong spatial contrast in the energy budget of snow-covered and snow-free areas may generate a significant advection of heat and moisture. Where forest cover is present, it alters snow accumulation and ablation processes, mostly by intercepting snowfall and modifying the surface micrometeorology. Intercepted snow can account for as much as 60% of annual snowfall in both boreal and maritime forests (Storck et al., 2002), while losses to sublimation can reach 30–40% of annual snowfall in coniferous canopies (Pomeroy and Schmidt, 1993).

Root distribution and maximum rooting depth are affected by plant age and biomass, soil texture and depth, and mean annual precipitation. The distribution plays an important role in determining various ecosystem processes including vegetation distribution, preferential water use, and coexistence of different vegetation types. The assumption that the root distribution profile and rooting depth do not change in time may be suitable for simulating energy and water balance dynamics of mature stands over a short period of time but is not expected to be optimum for dynamic vegetation models which are designed to capture the growth and death dynamics of vegetation. Based on stable isotope analysis, Weltzin and McPherson (1997) conclude that tree seedlings use a shallow source of soil water, while mature trees use deeper sources. Donovan and Elheringer (1994) find that the seasonal development of water stress in shrubs decreased with increasing size, age, and rooting depth. In the Arctic, as the frozen soil is thawed during the summer season, much soil water is accumulated near the 0°C front. When plants experience water stress during the summer season due to small precipitation, they access water from deeper soil layers due to their increased rooting depth and deeper root profiles.

**Objectives**

For all the reasons mentioned above, it is indispensable to establish the feedback mechanisms between the land and atmospheric part of the water and energy cycles in climate modeling. Thus, a coupled hydrological and biogeochemical model (CHANGE) is developed, which can account for the processes associated with energy and mass transfer in arctic regions. The major processes considered by CHANGE are the following: the exchange of energy, water, and CO₂ at the vegetation-soil-atmosphere interface under temporal and spatial heterogeneities, snow effects on water and energy fluxes, soil freezing and thawing, ice effects on soil water mobility, effects of soil organic matter on water and heat fluxes, dynamic root depth profile and distribution, and water uptake by plants.

The objectives of this study are to describe the entire processes of CHANGE and to test model simulations for water, energy, and CO₂ budgets in a boreal deciduous needle-leaf forest in eastern Siberia from 1986 to 2004.

**Participants**

**PI:** H. Park (JAMSTEC)

**Co-Is:** H. Yabuki, Y. Iijima (JAMSTEC), J. Walsh, Y. Kim, K. Saito (IARC)
Methodology

Model Description

CHANGE simulates energy, moisture, and momentum fluxes between the land and atmosphere, the hydrologic cycle, and soil temperature. The model provides a consistent treatment of energy exchange, ET, and carbon exchange by plants, by linking photosynthesis (Farquhar et al., 1980) with stomatal conductance (Collatz et al., 1991, 1992). The model represents spatial heterogeneity in land cover by dividing each grid cell into three land cover types: lake, wetland, and vegetation. The lake and wetland are not included now. The vegetated portion of the grid cell is further divided into a maximum of four patches of plant functional types (PFT). Multiple PFTs can co-occur in a grid cell. Each patch, while sharing the grid cell, is parameterized as a separate column for energy and water calculations. The details for the model structure are described further below.

Radiative transfer model

Vegetation canopies are very complicated in their structure. The canopy structure causes a distinct light environment on leaves, which nonlinearly contributes to biophysical processes. Thus light transfer through the canopy must be simulated to evaluate photosynthesis, stomatal conductance, and leaf and soil surface energy balance. Incoming hourly direct and diffuse radiation at the top of the canopy is estimated using daily solar radiation. The radiation attenuation and absorption by the canopy and soil surface is modeled separately for diffuse, direct, and photosynthetically active radiation (PAR) radiative fluxes.

Energy balance

CHANGE considered surface energy balance over the canopy and soil surface. In CHANGE, vegetation is represented by a single layer. The basic equation for the canopy surface energy balance is

\[ R_{n,c} = H_c + LE_c + \Delta S_c \]  

where \( R_{n,c} \) is the net radiation, \( H_c \) is the sensible heat flux, \( LE_c \) is the latent heat flux, and \( \Delta S_c \) is the head flux due to storage in the canopy air and biomass.

The governing equation for the energy balance over soil surface is

\[ R_{n,s} = H_s + LE_s + G + \Delta S_s \]  

where \( G \) is the ground heat flux, and the other components are the same in (1).

To close the energy budget for the vegetation-soil-atmosphere system, CHANGE solves separate energy balances for each of the surface parts, and then solves an overall balance. If snow is falling or is present in the canopy, the model does find a foliage temperature. Downwelling shortwave and longwave radiation from the sky is reduced or absorbed by the foliage. Longwave input to the understory is based on the foliage temperature. The ground snowpack surface and ground surface temperature are then solved. The energy fluxes from the over and understory are used to compute the canopy air temperature, which controls sensible heat exchange between the canopy and the atmosphere. Closing the energy balance improves the simulation of surface energy fluxes by including the interactions between the canopy and soil surface and ensures that reported surface energy fluxes were accurate (Cherkauer et al., 2003).

Aerodynamic resistance

Aerodynamic resistance is calculated separately for the overstory canopy and understory layers following the model developed by Heddeland and Lettenmaier.
The model assumes a logarithmic wind speed decay profile to the top of the canopy and an exponential decay profile within the canopy. A stability correction is included.

**Carbon and nitrogen cycling**

The main structure of carbon and nitrogen cycling in CHANGE is based on the ecosystem process model Biome-BGC (Thornton et al., 2002) although many of the specific algorithms have been extended and/or modified. The Biome-BGC simulates biogeochemical processes across multiple biomes. Carbon and nitrogen cycling associated with live vegetation and litter and soil layers is included. Carbon and nitrogen stores are partitioned into leaves, roots, stems, and coarse roots. Stem and coarse-root stores also include both live and dead wood components to account for differences in respiration and C:N ratios. The calculation of leaf photosynthesis is based on the Farquhar biochemical model (Farquhar et al., 1980). Leaf stomatal resistance, which is needed for the water flux, is coupled to leaf photosynthesis in a manner similar to Collatz et al. (1991).

**Snow accumulation and melt**

Snow accumulation and melt are simulated using a two-layer, energy and mass balance model. The energy balance components are used to simulate snowmelt, refreezing, and changes in the snowpack heat content. The mass balance components represent snow accumulation/ablation, changes in snow water equivalent, and water yield from the snowpack. The snowpack energy balance is given by Anderson (1972)

\[ c_s W \frac{dT_s}{dt} = R_n + Q_s + Q_p + Q_m + Q_z \]  

where \( c_s \) is the specific heat of ice, \( W \) is the water equivalent of the snowpack, and \( t \) is time. The energy exchange at the snow-air interface is given by \( R_n \), the net radiation; \( Q_s \), the sensible heat transfer by turbulent convection; \( Q_p \), the energy lost to evaporation and sublimation or the energy gained through the release of latent heat during condensation; and \( Q_m \), the heat advected to the pack by rainfall. \( Q_m \) is the internal latent heat lost by melting, or heat gained by refreezing of liquid water. Heat transfer by conduction from the snow-ground interface, \( Q_{gs} \), is neglected.

**Frozen soils algorithm**

The frozen soil algorithm represents the effects of seasonally frozen ground on surface hydrologic response and the surface energy balance. In CHANGE, the thermal and moisture fluxes are solved separately. The decoupling of the thermal and moisture flux solutions means that soil thermal fluxes can be solved at any number of nodes through the soil column. At each time step, thermal fluxes through the soil column are solved first. The estimated soil node temperatures are then used to predict the soil layer ice content. Subsequently, the matric potential in frozen soil is computed using the updated ice contents and liquid moisture content in unfrozen soil. Finally, soil thermal node properties for the next time step are estimated from the updated soil layer moisture and ice contents.

The heat balance equation with water phase change in soil used in the model is given by

\[ C_s \frac{dT}{dt} = \frac{\partial}{\partial z} \left[ k \frac{\partial T}{\partial z} \right] + \rho_i L_f \left[ \frac{\partial \theta_i}{\partial t} \right] \]  

where \( C_s \) is the soil volumetric heat capacity, \( T \) is the soil temperature, \( k \) is the soil thermal conductivity, \( \rho_i \) is the density of ice, \( L_f \) is the latent heat of fusion, \( \theta_i \) is the ice
content of the layer, and $z$ is the depth. The soil thermal flux predictions are based on temperatures at the surface ($T_s$), at the bottom of the first layer ($T_1$), and at the bottom of the soil column ($T_b$). An exponential temperature profile is assumed between $T_1$ and $T_b$, while $T_s$ is solved explicitly as a part of the surface energy balance. Thermal fluxes are solved numerically at an hourly time step via an infinite difference approximation of (4). Thermal conductivity and volumetric heat capacity of the soil layers are calculated at each time step from the revised soil water and ice contents, based on the algorithm provided by Farouki (1986). Parameterizations for the effect of soil organic matter on soil thermal and hydraulic properties are proposed by Lawrence and Slater (2008).

Vertical unsaturated water flow in homogeneous soil is simulated traditionally by combining the Darcy flow equation for unsaturated soil

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D(\theta) \frac{\partial \theta}{\partial z} \right) - \frac{\partial K(\theta)}{\partial z}$$

(5)

where $\theta$ is the volumetric water content, $D$ is the soil water diffusivity, and $K$ is the hydraulic conductivity. If appropriate time and depth increments in the calculations of (5) are chosen, (5) is numerically stable and accurate, but the strong nonlinearity inherent in (5) is very computer-time demanding.

An alternative and much more rapid approach is presented in Wind and van Doorne (1975). There model is based on the approximation

$$K(\psi) = K_s e^{\alpha \psi}$$

(6)

where $\psi$ is the soil water potential, $K_s$ is the saturated hydraulic conductivity, and $\alpha$ is a constant. Ice has a blocking effect on soil water flow. There impermeable fraction, $f_i$, is parameterized as a function of soil ice content (Niu and Yang, 2006)

$$f_i = \left\{ \exp \left[ -\eta \left( 1 - \frac{W_i}{W_s + W_i} \right) \right] - \exp(-\eta) \right\}$$

(7)

where $\eta$ is an adjustable scale-dependent parameter (= 3), and $W_i$ is the ice content. The hydraulic conductivity (6) is in turn defined

$$K(\psi) = (1 - f_i)K_s e^{\alpha \psi}.$$  

(8)

When there is a frozen layer present, it has an ice content based on the average temperature of the sublayer. The fraction of unfrozen water can be obtained by (Flerchinger and Saxton, 1989)

$$W_l = W_s \left( \frac{L_f T}{g \psi_e T} \right)^{B_p}$$

(9)

where $W_l$ is the liquid water content of soil layer, $W_s$ is the maximum water content of soil layer, $\psi_e$ is the air entry potential, and $B_p$ is the pore-size distribution. The phase transition alters the soil temperature by release or consumption of heat.

Water uptake by plants

A methodology for parameterizing root distribution as a function of root biomass is proposed by Arora and Boer (2003). In CHANGE, root distribution and rooting depth evolve and increase as root biomass increases. The root biomass is estimated by the ecosystem process model.

Forcing data

The meteorological data required in CHANGE are the routine observation datasets of the Baseline Meteorological Data in Siberia (BMDS). Using the daily forcing data, CHANGE estimates hourly, energy, water, and CO$_2$ fluxes.
Meteorological variables are interpolated every hour using some empirical methods with daily forcing data. The heat fluxes were found to be highly sensitive to solar radiation and temperature. Longwave radiation and vapor pressure follow their diurnal variations. In particular, air temperature greatly affects the Bowen ratio due to the dependence of the heat flux. The diurnal variation in air temperature is a typical pattern fixed by the observed daily mean, maximum, and minimum air temperatures.

**Activities for 2009FY**

CHANGE was applied to regions of different climate and land surface in order to test model simulations for water, energy, and CO₂ fluxes. As additional work, the model development was expanded to include parameterizations of moss and organic layers which greatly affect heat and water fluxes in arctic regions.

**Results of 2009FY**

Energy exchange at the land surface affects the local climate through the transfer of heat and water to the atmosphere. Therefore, differences in the energy partitioning between regions can lead to distinctly different local climates. Fig. 1 shows the comparison between simulation and observation of energy fluxes in Yakutsk. The comparison indicates that CHANGE simulates well seasonal variation of energy fluxes. However, there is a tendency in the model to underestimate energy fluxes under cloudy or rainy conditions. This seems to be related to the prediction of downward longwave radiation, not considered the cloud effect on the radiation. $R_n$ exhibits a seasonality that steeply increases in spring and decreases in autumn. The seasonal trends of $LE$ and $H$ follow the parabolic rise and fall of $R_n$. $H$ in spring is higher than $LE$. Therefore, the spring Bowen ratio is greater than one. The maximum $LE$ occurs immediately after the peak of $H$. Although the amplitude in seasonal variation of $G$ is small compared to other components, the peak of $G$ occurs just after snowmelt.
**Fig. 1.** Comparison between simulation (lines) and observation (dots) of energy fluxes in Yakutsk.

Figure 2 displays daily observed and simulated snow depth and soil temperature and water amount at different depths. CHANGE simulated well the timing of snow accumulation and snowmelt during the selected period. The snow processes are complexly interrelated to radiation and energy budgets and soil temperature. Therefore, the good performance for the snow processes means that CHANGE expressed other processes related to snow processes. Snow has an insulating effect reducing soil cooling. The insulating effect of snow is found in soil temperatures. The inter-annual variability of soil surface temperature corresponds to that of snow. A representative example for the snow insulating effect on soil temperature is found in 2006 when CHANGE underestimated snow depth. The underestimation of snow depth caused the temperature at 80 cm depth to cool down.
CHANGE well reproduces soil temperatures at two depths. While the overall predictions are satisfactory, there are some weaknesses. As compared to the soil temperatures observed, CHANGE sometimes heats the soil in the summer. The phenomenon is found in the deep soil. However, the good reproduction of the model to soil temperatures indicates that the parameterizations of thermal conductivity and volumetric heat capacity considered the effects of soil freezing to be useful. Furthermore, the reproduction implies the availability of the parameterizations of soil organic matter. CHANGE also captures well seasonal and inter-annual variations of soil moisture, although there are some weaknesses. For instance, soil moisture of the surface layer (-0.1 m) is sometimes overestimated. The influence of the overestimation is found at the soil layer below the surface. The higher soil moisture at snowmelt season is a specific characteristic in arctic regions. The prediction of soil moisture during the snowmelt matches well with the observations. The simulated soil moisture responds well to precipitation events at the surface as well as deep soil layers. This primarily implies that the parameterization of the blocking effect of ice on water flow is available. However, the large difference between simulations and observation in soil moisture at the soil layers requires more modification for the soil moisture scheme.

Fig. 2. Comparison of snow depth, soil temperature, and soil moisture to observations.
The simulated soil temperature and moisture are compared to the values observed at Pokrovsk near Yakutsk. The simulations are in good agreement with the observations. CHANGE captured well the interannual variation of soil temperature in the winter season, which is greatly dependent on snow depth. For instance, when snow depth is shallow, soil becomes cool. The variation of minimum soil temperature during winter is well predicted by the model. On the other hand, the soil temperature during summer displays stable variations in both observation and simulation. This is probably due to the influence of less change of leaf area index. In case of soil moisture, the absolute value of soil moisture is clearly different between simulation and observation, which is related to the difference in the soil hydraulic parameters associated with different places. However, CHANGE captured well the response of soil moisture to precipitation events over 3 years. Finally, these good predictions increase the generality of CHANGE.

Presentations
H. Park, Y. Iijima, H. Yabuki, T. Ohata. Evaluation of long-term water, energy, and CO2 budget at two Arctic sites with a coupled hydrological and biogeochemical model. JPGU, Makuwari, Japan, May.
H. Park, Y. Iijima, H. Yabuki, T. Ohata. Modeling water, energy, and CO2 fluxes in Arctic region with a coupled hydrological and biogeochemical model. MOCA-09, Montreal, Canada, July.

Publications
Theme 10: Arctic System Modeling

Introduction

IARC has been facilitating development of an Arctic System Modeling activity, and has sponsored three workshops for the development of an implementation strategy. Various modeling activities are underway in JICC themes, providing potential contributions of component models for an Arctic System Model. Several JICC themes also include observations and measurements that can be utilized in system model development and testing. Particular IARC/JAMSTEC contributions to an Arctic System Model lie in our land surface modeling (centered at JAMSTEC, H. Park) and in our Arctic ocean/ice/biogeochemistry modeling (centered at IARC, Deal/Jin/Watanabe/McRoy). Background on each of these two activities follows.

For climate system understanding, it is essential to capture the feedback mechanisms between the land and atmospheric part of the water and energy cycles in climate modeling. Thus, a coupled hydrological and biogeochemical model (CHANGE) is being developed, which can account for the processes associated with energy and mass transfer in arctic regions. The major processes considered by CHANGE are the following: the exchange of energy, water, and CO₂ at the vegetation-soil-atmosphere interface under temporal and spatial heterogeneities, snow effects on water and energy fluxes, soil freezing and thawing, ice effects on soil water mobility, effects of soil organic matter on water and heat fluxes, dynamic root depth profile and distribution, and water uptake by plants.

Marine ecosystem modeling for the Arctic is essential to validate the seasonal succession of primary production in sea ice, the Arctic Ocean and its peripheral seas. It also aids in identifying key ecosystem controls (light, nutrients and physical processes) and their relative importance in different regions at different times of the year. Ecosystem modeling can guide the priorities for observations through identification of key parametric uncertainties in a model. Finally, long-term ice-ocean ecosystem model runs can enable investigations of ecosystem responses to climate change in the polar regions. Our marine biogeochemistry modeling is motivated by all these possibilities.

Objectives

The main goal of an Arctic System Modeling project is to produce a modeling system for the Arctic, enabling investigations of arctic climate variability and change as well as their potential impacts on humans, ecosystems, and the global system.

A key goal of the Arctic System Modeling project is to develop a land surface model, evaluating changes in land surface processes caused by climate change and deformed land surface in the arctic region. The immediate scientific objectives of the land surface modeling component of Theme 10 are (a) to evaluate the performance of the land surface model mainly dealing with biogeophysical and hydrological processes at the surface and sub-surface of land, including water and heat exchange with snow cover and/or atmosphere, water phase change, and carbon flux; (b) to improve the formulation of the roles of moss and organic layers to water and heat flows; and (c) to evaluate the dynamics in land surface processes following vegetation restoration after forest fire in Alaska.

The marine biogeochemistry modeling activity is intended to contribute to development of marine biochemistry and arctic ocean/sea ice modules for an Arctic System Model. An immediate objective of this activity is to evaluate the response of
lower trophic production to climate change in the Pacific subarctic seas (e.g., the Bering Sea).

Participants
John Walsh (IARC) and Hotaek Park (JAMSTEC) are Theme leaders at their respective institutions. Other participants are Clara Deal (IARC), Meibing Jin (IARC), Peter McRoy (IARC), and Eiji Watanabe (IARC).

Methodology
The general plan for Theme 10 is guided by the following methodological considerations:

1. Follow the implementation plan for ASM.
2. Identify JAMSTEC and IARC modeling participants.
3. Modify existing components of land surface, marine biochemistry, and ocean/ice models to conform to ASM modularity.
4. Implement JAMSTEC/IARC land surface, marine biochemistry and ocean/ice modules into an ASM coupler when the coupler is established.

For land surface modeling, a coupled hydrological and biogeochemical model (CHANGE) is used in order to evaluate the influences of understory vegetation on water and energy budgets. CHANGE simulates energy, moisture, and momentum fluxes between the land and atmosphere, the hydrologic cycle, and soil temperature. The model provides a consistent treatment of energy exchange, ET, and carbon exchange by plants, by linking photosynthesis (Farquhar et al., 1980) with stomatal conductance (Collatz et al., 1991, 1992). The model represents spatial heterogeneity in land cover by dividing each grid cell into three land cover types: lake, wetland, and vegetation. The lake and wetland are not included now. The vegetated portion of the grid cell is further divided into in maximum four patches of plant functional types (PFT). Multiple PFTs can co-occur in a grid cell. Each patch, while sharing the grid cell, is parameterized as a separate column for energy and water calculations. The details for the model structure are described further in below. The more description of CHANGE refers to the report of Theme 9-1.

For the marine biogeochemistry modeling, the methodology is to implement a 1-dimensional model, test it against observational data for particular regions (e.g., the Bering Sea), and then couple a spatially distributed version of the model to an ocean/ice model.

Activities for 2009FY
For the land surface modeling, the main activities for FY2009 were the improvement of the land surface model, particularly its handling of moisture and the surface-atmosphere moisture transfer (via evapotranspiration). We have implemented the model over Siberia, and validated its simulation of evapotranspiration against eddy-correlation measurements made by JAMSTEC collaborators over the same region.

For the marine biogeochemistry modeling, we have implemented the module for primary production in the Bering Sea, and have validated it against (a) daily SeaWiFS data and (b) mooring fluorescence data. We have also undertaken simulations of spatially distributed algal biomass in the waters surrounding Alaska. Collaboration with Peter McRoy has been initiated during the past year as Dr. McRoy joined the IARC faculty. In addition, eddy-resolving simulations of the Arctic Ocean peripheral
seas (Beaufort/Chukchi) have been carried out by E. Watanabe (IARC). This module can serve as a high-resolution platform for coupling with the marine biogeochemistry model and, eventually, the land surface model described above.

Results of 2009FY

Results are presented below first for the land surface modeling, then for the marine biogeochemistry modeling.

Figure 1 shows the inter-annual variations of total evapotranspiration (ET), evaporation from overstory and understory vegetation, and evaporation from soil surface in an eastern Siberian larch forest over 19 years. The simulated ET distributed, on average, around 160 mm/year. An observation (Ohta et al., 2008) using an eddy correlation system over 1998 to 2006 found that annual ET in an eastern Siberian larch forest was distributed at 169–220 mm. The simulated ET is significantly low compared to the reported observation (Ohta et al., 2008). The CHANGE also simulates that evaporation (e.g. = transpiration + canopy interception) from the overstory vegetation occupies about 45% of total ET. The remaining 55% is partitioned to evaporation from understory vegetation and soil evaporation. Iida et al. (2009) analyzed ET measured by eddy correlation systems at both overstory and understory of an eastern Siberian larch forest and found that evaporation from understory occupied about 55% of ET. The simulated ratio of understory evaporation is perfectly consistent with the results of Iida et al. (2009). However, there is a difference in the absolute value of understory evaporation between this simulation and the observation of Iida et al. (2009). CHANGE estimated 85 mm of annual understory evaporation, while Iida et al. (2009) observed about 100 mm/year. The underestimation by CHANGE seems to have contributed to the underestimate of ET. On the one hand, CHANGE adopted a scheme for transpiration in which water uptake by plant roots is dependent on root density estimated by the model itself. The underestimate of root density by the model is an additional reason of the underestimated ET (data not shown). Although there are some weaknesses, the CHANGE clearly demonstrates that evaporation from the understory vegetation plays an important role in water fluxes of arctic regions.
Fig. 1. Inter-annual variation of simulated evapotranspiration, evaporation from overstory and understory, and evaporation from soil surface.

References

In the marine biogeochemistry modeling work, lower trophic level production in the Bering Sea has been assessed with a vertically one-dimensional (1-D) coupled ice-ocean ecosystem model, which was applied to data collected by a National Oceanic and Atmospheric Administration (NOAA)/Pacific Marine Environmental Laboratory (PMEL) mooring from 1995 to 2005. The physical model is forced by sea surface winds, heat and salt fluxes, tides, and sea ice. The biological model includes coupled pelagic and ice algae components. Model results are validated with daily mooring temperature, fluorometer, and daily Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll data. Two distinct ocean conditions and phytoplankton bloom patterns are related to the Pacific Decadal Oscillation (PDO) Index regimes: warmer temperature and later warm-water phytoplankton species bloom in PDO > 1 year; colder temperature and earlier cold-water phytoplankton species bloom in PDO < -1 year. Productivity of different phytoplankton species changed dramatically after the 1976 climate shift, but the total annual net primary production (NPP) remained flat over the past four decades under similar nutrient regulation. Climate shift also affected the vertical distribution of lower trophic level production and energy flow to the upper ocean pelagic ecosystem or the benthic community. A long-term PDO
regime shift occurred in 1976, and a short-term PDO reversal occurred in 1998. Phytoplankton biomass responded promptly to both short- and long-term climate changes. Zooplankton biomass responded more to the long-term than to the short-term climate shift. The model results captured observed trends of zooplankton abundance changes from the 1990s to 2004.

An ice ecosystem model was coupled to a global dynamic sea ice model to assess large-scale variability of primary production and ice algal biomass within arctic sea ice. The component models are the IARC ice ecosystem model (Jin et al. 2006, 2007; Lee et al. submitted) and the Los Alamos National Laboratory sea ice model, CICE. The coupled model results help fill in the spatial and temporal gaps between very sparse regional observations of ice algal biomass and productivity. Simulated total annual primary production within arctic sea ice was 15.1 Tg C; within the range of 9 to 73 Tg C estimated using in situ data. The amount of C fixed was > 3 Tg C mnth$^{-1}$ for March, April, and May. The Bering Sea, Arctic Ocean basins, and the Canadian Archipelago were the most productive regions on an annual basis, contributing approximately 24%, 18%, and another 18% of the total primary production, respectively. High production in the Bering Sea was due to high daily production rates, while the large sea ice extent in the Canadian Archipelago and, in particular, the Arctic Ocean basins resulted in their considerable contribution to sea ice primary production. Trends, patterns, and seasonality of the simulated results for ice algal biomass and primary production agree reasonably well with limited observations. In the model, ice growth rate controls the availability of nutrients to sea ice algae and thus ice algal growth. The numerical model results suggest that ice melting rate, which determines the proportional rate of ice algal release, controls the timing of maximum ice algal biomass. Rapidly decreasing ice algal productivity is followed by a more gradual decline in biomass over large areas. The model described brings us closer to including the role of sea ice algae in C flux and biogeochemical cycling within global climate and arctic system models.

Finally, the high-resolution ocean/ice model developed by E. Watanabe has been applied to the Beaufort/Chukchi shelf region. The model simulates mesoscale eddies realistically when forced by reanalysis-derived winds. Tracer experiments were also performed to track the fate of Pacific water that enters the Arctic through Bering Strait. According to the model results, the eddies along the shelf break are responsible for the major portion of the transport of Pacific water from the Alaskan shelves into the Arctic Ocean. This result has important implications for Arctic System Modeling, as it indicates that the ocean model must have high resolution (finer than 10 km) in order to capture the water mass budgets of the Arctic Ocean.
Beaufort Shelfbreak Eddies

Fig. 2. Eddies along the Alaskan shelf break as simulated by the high-resolution ocean model (E. Watanabe, IARC).

References

Presentations


Publications


**Theme 11: Atmospheric processes**

**Participants**
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Co-Is: D. Atkinson, J. Walsh (IARC), Y. Tachibana (JAMSTEC)
J. Malingovsky

**Methodology**
Atmospheric polar amplification mechanisms are investigated in models from simple conceptual box models to 3D GCMs. An observational study of the dynamics of near-surface inversions in Fairbanks has been conducted in a set of radiosonde launches. Surface inversion is an important feature of the arctic atmosphere controlling the exchange processes between the surface and the free atmosphere.

**Activities for 2009**
Polar amplification mechanisms have been studied using a simplified atmospheric GCM coupled to an upper mixed layer ocean with and without continents. The role of continents and seasonality is under investigation. It was shown that atmospheric heat transport plays an important role in forming the polar amplification pattern in a model without any surface albedo feedbacks.

Balloon launches were performed every two to three hours between sunset and sunrise on February 24, April 5, April 7, May 1, October 13, October 15, and November 21, 2009. Preliminary results suggest a steepening of the surface-based temperature inversion until the surface temperature reaches a minimum temperature, when the temperature inversion becomes deeper with height.

**Results for 2009**

Atmospheric polar amplification mechanisms in an idealized GCM

*Introduction*
Surface albedo feedback (SAF) is believed to be the main mechanism for polar amplification (PA) of global warming. However, even in the absence of any sea ice and surface albedo feedback, significant polar amplification was obtained in 2xCO2 runs on an aquaplanet (Alexeev, 2003; Langen and Alexeev 2005; Alexeev et al., 2007, Langen Alexeev 2007). The driving mechanism responsible for PA was identified: an increase of the atmospheric heat transport in the warming climate, primarily due to the increase in the latent heat transport from the tropics to the high latitudes. This mechanism was studied in detail in the articles quoted above using idealized box models and aquaplanet GCMs. This study concentrates on studying the effects of continents and seasonality on the PA pattern.

*Idealized ‘wet’ continent experiment*
We will first place an idealized continent in our aquaplanet model. The albedo feedback is still turned off; all the points have the same albedo; there is now ice in water points and no snow is formed on the surface. The continent points have 100% wetness. The difference between ocean and continent points is their heat capacity; the continent points have 10 times lower heat capacity compared to the ocean points. The ocean points’ heat capacity corresponds to the heat capacity of the 50m deep ocean upper-mixed layer (Fig.1).
The model is first run to equilibrium with a seasonal cycle and standard CO₂ concentration (360ppm). The CO₂ concentration is then increased instantly and the model is run again until reaching a new warmer equilibrium (2xCO₂ climate). The zonal mean 2xCO₂ response now has strong seasonality and is quite different over sea and land points (Fig. 2).

Fig. 2. Winter and summer 2xCO₂ response in an idealized ‘wet’ aquaplanet experiment.

The winter warming over continents is significantly stronger than the ocean warming. Another striking result is that summer warming is significantly suppressed compared to winter warming over the continent and even compared to sea warming. These results are quite surprising because the SAF is turned off. The PA pattern is obtained solely due to atmospheric mechanisms.
Idealized ‘wet’ continents experiment with ‘realistic’ configuration of topography

In the next experiment, we keep the continents wet and flat but use the present-day land sea mask. The model is again run to equilibrium and the CO$_2$ concentration is doubled instantaneously for our global warming experiment. All the surface points have the same fixed albedo.

The obtained modeled annual mean temperature change for both hemispheres is shown in Fig. 3 (left column). The modeled temperature change is compared with the temperature trend over 1960–2008 calculated from NASA GISS climatology (www.giss.nasa.gov). It is interesting to note that the idealized model captures the pronounced warming over Eurasia. This warming almost entirely consists of winter warming, as observed (not shown here). Even more surprising is that the maximum of warming in the Southern Hemisphere is located at the Antarctic Peninsula. Again, all the surface points have the same fixed albedo, there is no sea ice in the model, and no snow is formed at the surface. This leads us to conclude that these are purely atmospheric polar amplification mechanisms. The dynamics of these features have not yet been studied. We plan to do this work in the future.

Fig. 3. Idealized ‘wet’ continents experiments (2xCO2 – 1xCO2 temperature change, left column) compared with NASA GISS climatology, 1960–2008.

References


**Study of the dynamics of inversions in the Fairbanks area**

An observational program, initiated in spring 2009 and concluded in fall 2009, used weather balloon launches performed every 2 to 3 hours between sunset and sunrise to investigate how the surface-based temperature inversion evolves between the standard twice-daily NOAA weather balloon launches in Fairbanks, AK. A goal of this project is to explain the evolving patterns of the surface-based temperature inversion in terms of various physical and synoptic factors, such as wind, incoming solar radiation, and sun angle. The spring and autumn seasons were chosen for this study because there is a defined diurnal effect in the evolution of the surface-based temperature inversion at those times of the year. In winter in Interior Alaska, changes in the surface-based temperature inversion are dependent solely on synoptic pattern changes. Clear skies and calm winds throughout the night were required for the case study in order to isolate a radiationally-induced surface-based temperature inversion and to be able to ignore the dynamic effects of inversion formation.

Launches were performed every two to three hours between sunset and sunrise on February 24, April 5, April 7, May 1, October 13, October 15, and November 21, 2009. These case studies have all been treated separately because synoptic conditions, amount of sunlight, and strength of radiation vary per case, even though all cases had mostly clear skies and calm winds at the surface during the period of study. Preliminary results suggest a steepening of the surface-based temperature inversion until the surface temperature reaches a minimum temperature, when the temperature inversion becomes deeper (dz) with height. The results from the extra balloon launches will be compared with a simple surface radiation balance model to isolate wind-induced diabatic effects in the profiles. Further results will follow in the next report.

![Figure 1](image_url)

**Fig. 1.** October 13, 2009, observations. Temperature (°C) vs. height (m) up to 2000m is shown on the left, while wind speed (kt) versus height (m) up to 2000m is shown on the right.
A comparison of Arctic and Antarctic climate change

In activities aimed at syntheses of climate change information for the polar regions, J. Walsh prepared a paper comparing recent and projected changes of Arctic and Antarctic climate (Walsh, 2009, *Antarctic Science*). He was also a co-author of the Atmosphere section of “Arctic Report Card 2009,” which will appear in *State of the Climate: 2009*, to be published in the Bulletin of the American Meteorological Society. Finally, Walsh was the lead author of “Arctic climate: past and present,” which is undergoing review as Chapter 2 of *SWIPA* (Snow, Water, Ice and Permafrost in the Arctic), an assessment report now in preparation by the Arctic Monitoring and Assessment Program.

**Presentations**


**Publications**

